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THE ENGLISH ELECTRIC JOURNAL

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510 ARCTIC BUILDING, SEATTLE, WASHINGTON.
Telephone: SENECA 6323

VOLUME THIRTEEN • NUMBER ONE • MARCH 1953

R v.13 1953-54

Text

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One of the sixty-three 3,600 *h.p.* 3,000 *volts D.C. locomotives which are being built for the Spanish National Railways*

3,600 H.P. 3,000 Volts Direct Current Locomotives for the Spanish National Railways

ON MARCH 30TH, 1950, a contract was signed in Madrid between the Red Nacional de los Ferrocarriles Espanoles (RENFE) and the English Electric Export and Trading Company (a subsidiary of The English Electric Company Limited) for the supply of 20 complete 3,600 h.p. 3,000 volts D.C. electric locomotives and a number of partial equipments. The number of complete locomotives ordered was subsequently increased to a total of 63, the partial equipments being deleted. These locomotives, which are the most powerful of their type manufactured to date in Great Britain, are being built by The English Electric Company Limited and The Vulcan Foundry Limited, the former company being responsible for the design and construction of electrical equipment and the latter for the mechanical parts.

The new locomotives, the first of which have now arrived in Spain, are being built for the operation of freight and passenger trains on the Oviedo-Leon-Ponferrada section of the former Northern Railway (Fig. 1). This section serves one of the most important industrial areas in Spain and carries a heavy mineral traffic.

Initially, the locomotives will operate on the Ujo to Busdongo section of the Oviedo-Leon line, which has been electrified at 3,000 volts D.C. The remainder of the route is now being equipped for 3,000-volt operation. The Ujo-Busdongo section is 38 miles in length and is one of the most difficult main line sections in Spain with a practically continuous ruling gradient of 1 in 50 (2%) and sharp curvature through the Cantabrian mountains. The difficult nature of the country traversed by the Ujo-Busdongo line may be appreciated from the fact that it includes 70 tunnels aggregating 16 miles in length, and 156 bridges.

The introduction of these modern and powerful locomotives, with their exceptional tractive capacity, will enable the movement of heavy mineral traffic over these sections to be considerably expedited.

GENERAL DESCRIPTION

The locomotive superstructure (Figs. 2, 3 and 4) is streamlined with a driving cab at each end, mounted at the rear of each nose-end compartment. Within the superstructure the equipment is symmetrically disposed, with a 20 kW motor-generator-blower set and two cubicles containing the main control equipment at each end. In the centre of the locomotive are four frameworks containing the main starting resistances.

The driving cabs have two wide front windows with one fixed and one drop window at each side. The driving position is on the right-hand side of the cab. An upholstered seat is provided capable of vertical and horizontal adjustment.

The equipment is designed to operate on 3,000 volts, and current is collected by either one or both pantographs mounted on the roof.

The bogies are of the swing bolster equalised type but are not articulated. The tractive effort is transmitted through the bogie king pins and underframe to the draw gear.

All six axles are motored. Air, vacuum and regenerative braking are provided, the vacuum braking being used on the rolling stock only.

Principal Dimensions and Data

Gauge	5 ft 6 in (1676 mm).
Type of locomotive	General purpose.
Horsepower of locomotive :—	
1-hour rating	3600 h.p.
continuous rating	3000 h.p.

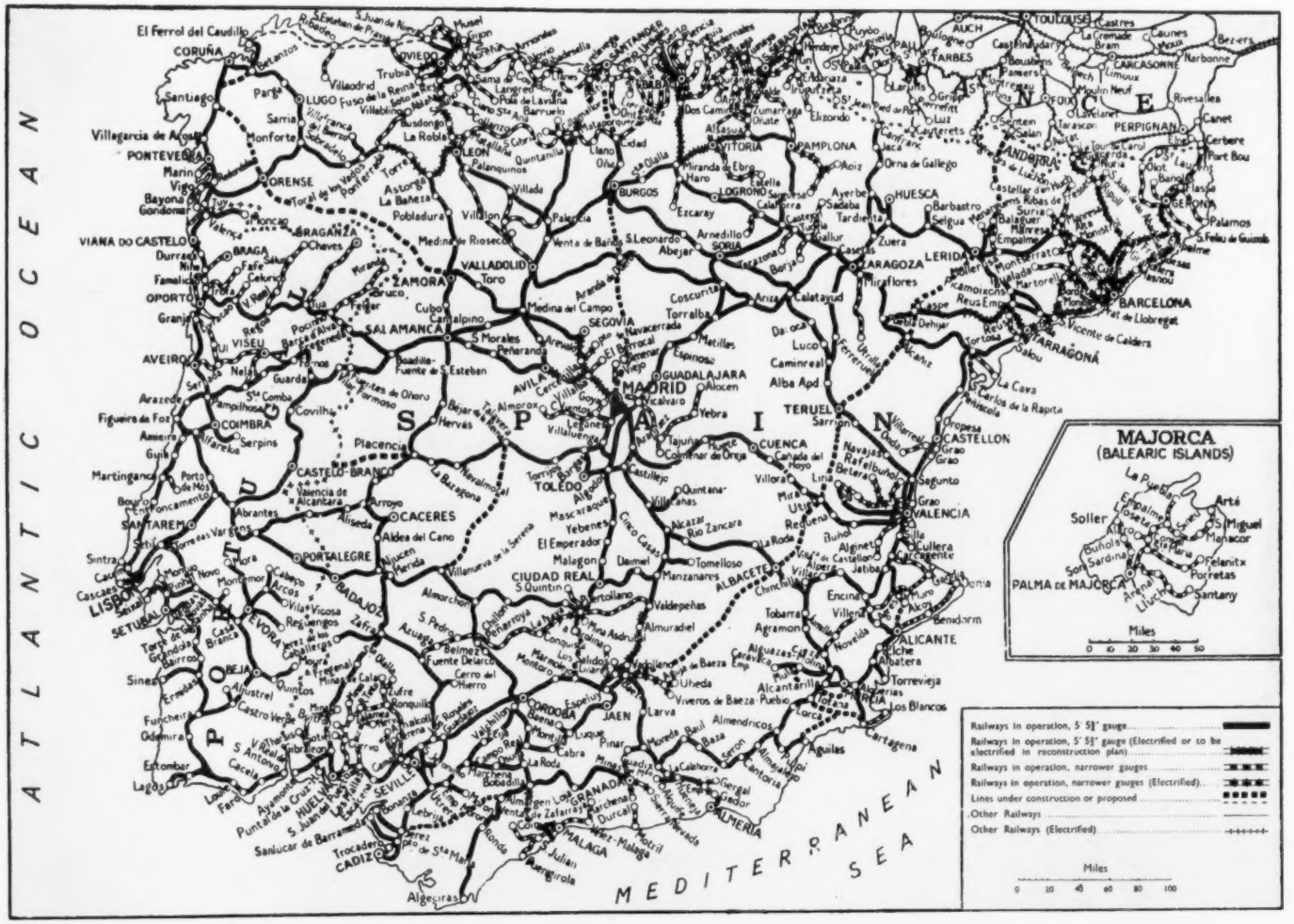


Fig. 1. The railways of the Iberian Peninsular. All the principal Spanish and Portuguese lines are of broad gauge, involving a break of gauge at the French frontier. Proposed railways, gauges and electrified routes are separately indicated

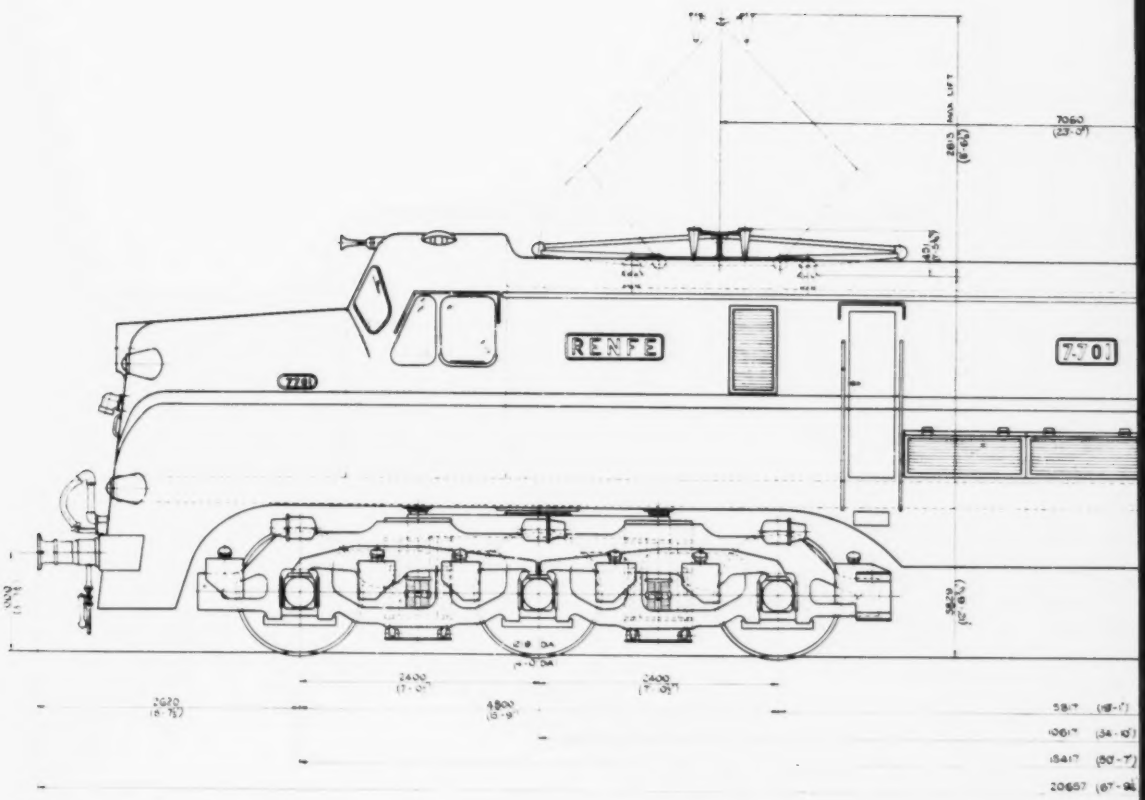
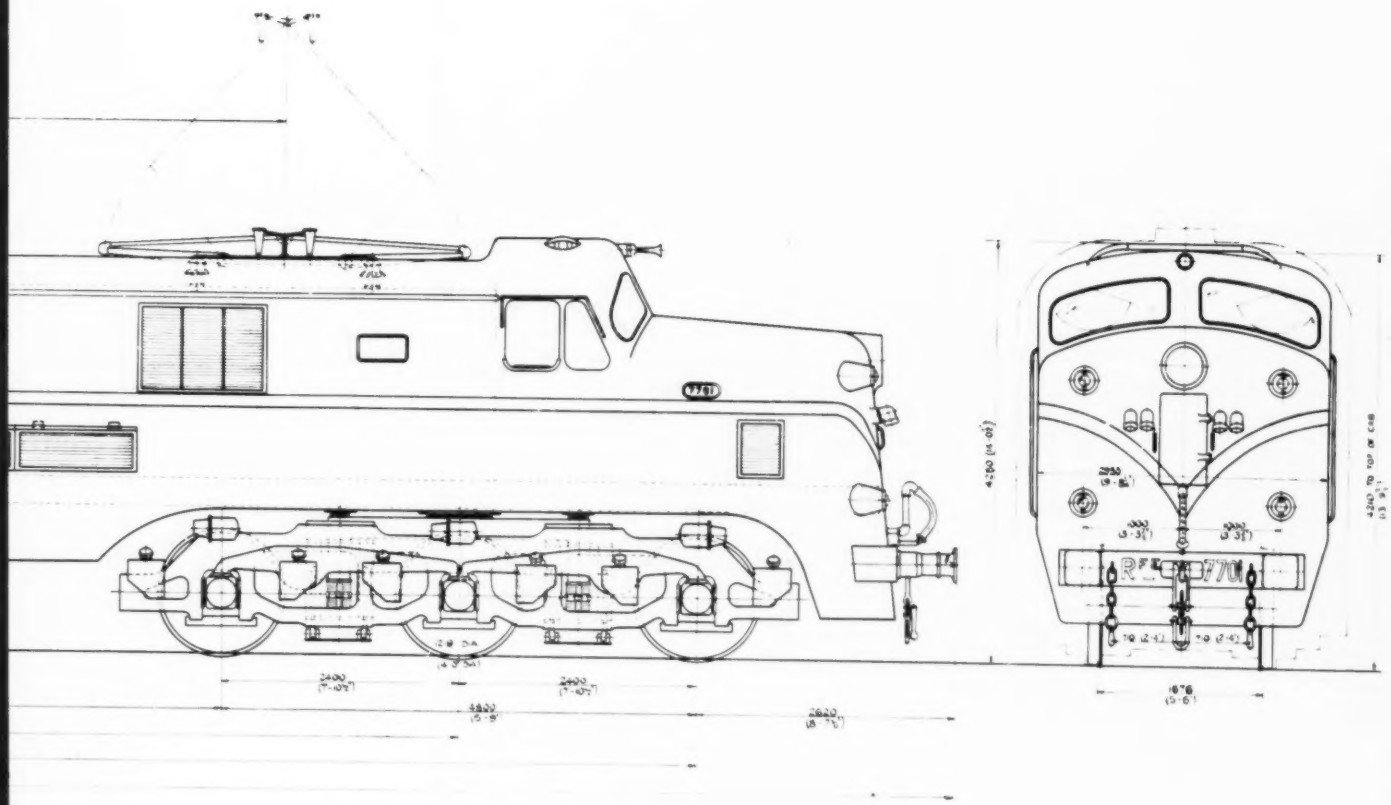


Fig. 2. Outline of



he 3,600 h.p. 3,000 volts D.C. locomotives

Maximum permissible speed	68.3 m.p.h. (110 km.p.h.).
Wheel arrangement	Co-Co.
Weight of locomotive in running order	118 tons (119,8 tonnes).
Weight of bogie in running order	32 tons (32,5 tonnes).
Weight per axle	19.6 tons (19,9 tonnes).
Wheel base of bogie	15 ft 9 in (4800 mm).
Wheel base of locomotive	50 ft 7 in (15417 mm).
Distance between king pins	34 ft 10 in (10617 mm).
Wheel diameter (new)	4 ft 0 in (1220 mm).
Length over buffers	67 ft 9¾ in (20657 mm).
Maximum width	10 ft 1 in (3073 mm).
Maximum height (pantograph housed)	14 ft 0½ in (4280 mm).
Maximum operating height of pantograph	20 ft 8 in (6,3 metres).
Minimum operating height of pantograph	14 ft 6 in (4,42 metres).
Minimum curve negotiable	525 ft (160 metres).
Clearance to rail, with new wheels	7 in (178 mm).
Clearance to rail level, with maximum permissible wheel wear	5.9 in (151 mm).
Locomotive brake equipment	Compressed air and electric regenerative.
Train brake equipment	Vacuum.
Line voltage—maximum	3650 volts.
Control voltage	110 volts.
Number of traction motors	6.
Type of traction motor	EE.514/1B.
Horsepower of traction motor :—	
1-hour rating	600 h.p.
continuous rating	500 h.p.
Gear ratio	63/16.
Ventilation of traction motors	Forced.
Starting resistance, type	Strip wound on edge.
Number of running notches	9.
Number of electric braking notches	13.
Tractive effort :—	
maximum at 25% adhesion	66000 lb (30000 kg).
1-hour rate at 34 m.p.h. (55 km.p.h.)	38280 lb (17400 kg).
continuous at 36 m.p.h. (58 km.p.h.)	30360 lb (13800 kg).

Layout of Equipment

The arrangement of the equipment in the locomotive is shown in Fig. 4.

NOSE ENDS

The nose ends of the locomotive each accommodate a motor-driven compressor, a motor-driven exhauster, one half of the lead-acid battery and various items of control equipment associated with these.

In addition, the nose at No. 1 end houses an L.V. equipment case containing the contactors controlling No. 1 compressor and exhauster motors, and half of the regenerative exciter field contactors. Another case contains resistances for the fields of the regenerative exciter, the compressor motor and the exhauster motor. Separately mounted on the rear wall are the low pressure air and vacuum switches and the compressor governor.

The L.V. equipment case in No. 2 nose end houses the controlling contactors for No. 2 exhauster and compressor motors in addition to a number of relays and resistances for brakegear control and battery charging. Accommodation is also provided in No. 2 nose for the exhauster cut-out switch, the voltage regulator and a case containing resistances for the No. 2 end auxiliary machines.

DRIVING CABS

No. 1 end driving cab is fitted with a controller together with the necessary brake valves and driving instruments, a driver's locker and an apparatus cupboard containing a number of control-gear switches and fuses. Mounted separately on the rear wall is a pantograph emergency lowering cock.

A door in the right hand rear corner provides access to a passage leading to the back of No. 3

equipment frame. A door in the left hand rear corner opens to a corridor through the main equipment compartment leading to a door into No. 2 cab.

The cab at No. 2 end of the locomotive is the master cab and in addition to accommodating a controller, brake valves and gauges similar to those in No. 1 cab, it has on the rear wall a cupboard containing the battery ammeter and voltmeter and the remainder of the switches and fuses not housed in No. 1 cab.

Separately mounted on the rear wall are the pantograph selector cocks, the pantograph reservoir screw-down valve, a foot operated air pump for raising the pantograph when the main air supply is not available and an emergency lowering cock for the pantographs.

Apparatus Compartments

A motor-generator-blower set is mounted in a compartment behind each driving cab.

The machine at No. 1 end supplies the field excitation for all the traction motors during regeneration and also the cooling air for the three traction motors in the bogie at that end of the locomotive.

The traction motor cooling air is drawn in through louvres in the side of the locomotive to a settling chamber and then passes through ducting to the traction motors.

The ventilating air for the M.G. set is drawn in through a separate louvre in the side of the locomotive and passes across the gangway to a second louvre in the wall of the M.G. compartment. Part

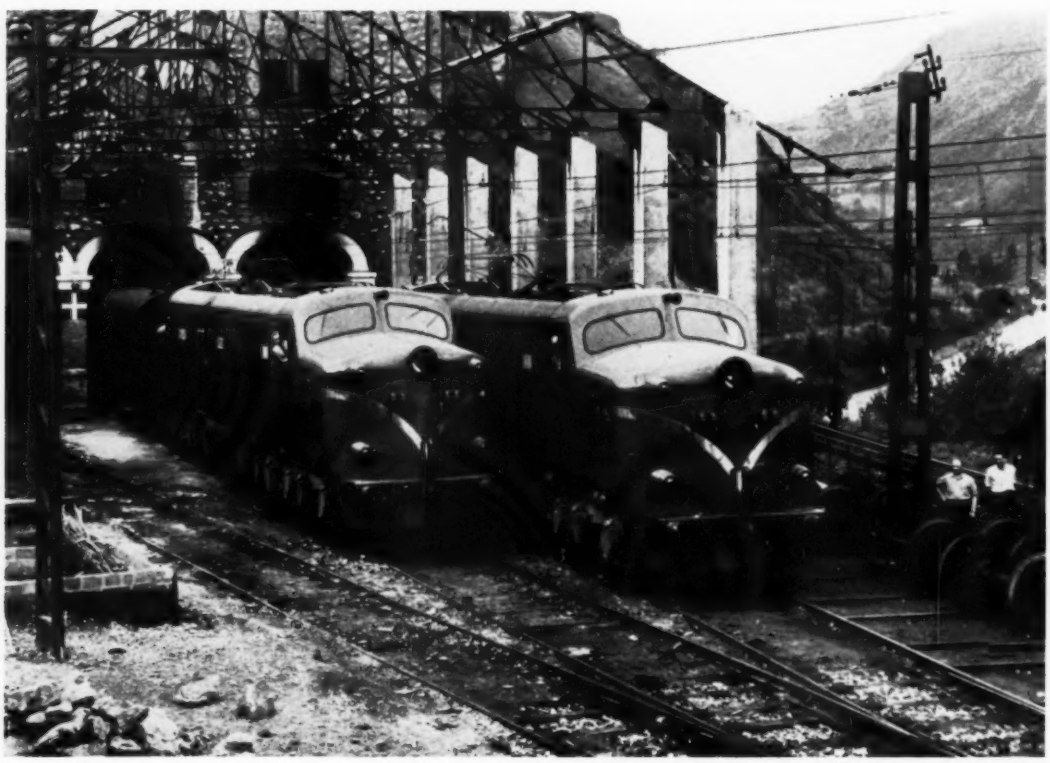


Fig. 3. Two of the locomotives in service

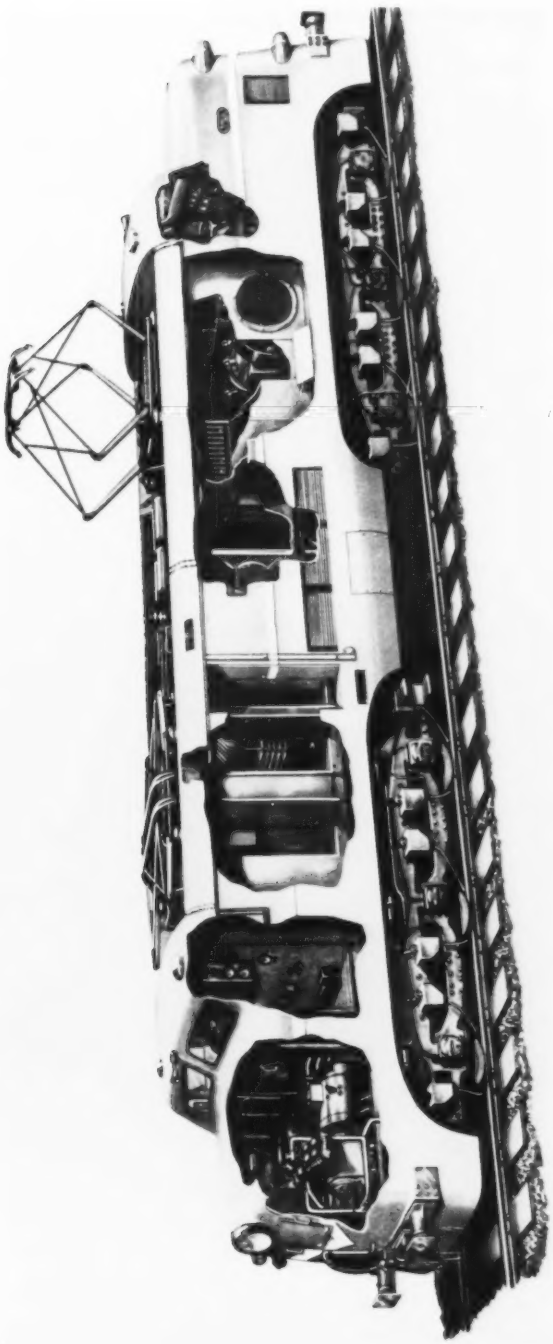


Fig. 4. Cut-away view of locomotive, showing arrangement of equipment

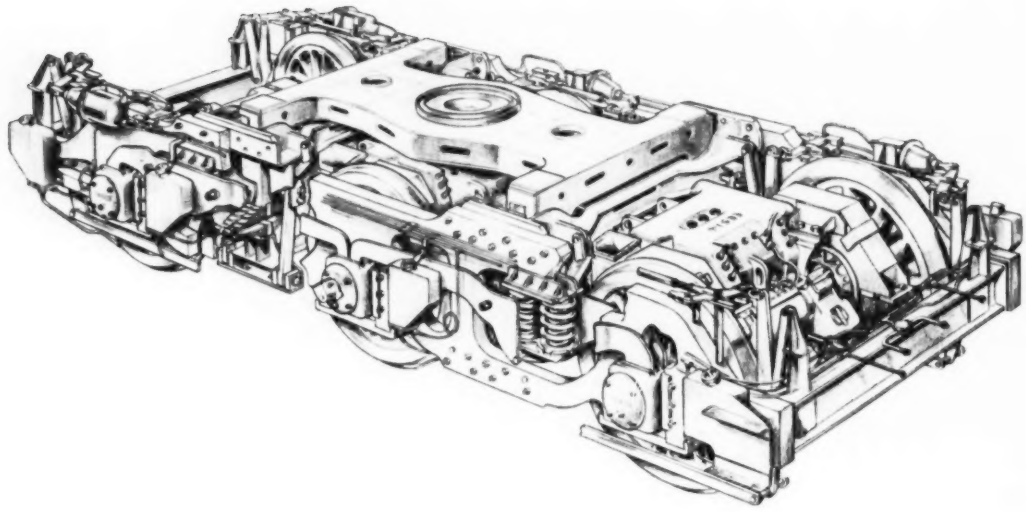


Fig. 5. General arrangement of bogie

of the air supply is expelled from the machine to the track and part is ducted to the nose compartment where it is expelled through a louvre in the side of the locomotive.

The machine at No. 2 end of the locomotive supplies all the low voltage circuits and also the ventilating air for the traction motors on No. 2 bogie. The arrangement of the cooling air paths for the M.G. set and the traction motors is similar to that provided at No. 1 end.

The contactors, group switches etc. of the control apparatus are mounted on frames housed in four sheet metal cubicles disposed in the superstructure as shown in Fig. 4. The cubicles have covers secured by spring catches which permit easy removal.

The main resistances are located on each side of the centre portion of the superstructure, and louvres placed below the waist line of the superstructure admit cooling air to them. Openings in the roof exhaust the flow of air as the resistances become hot.

Safety Doors

In order to ensure a measure of safety to personnel, the doors giving entry to the M.G. compartments at each end of the locomotive, and also the door leading to the passage between control frames Nos. 1 and 2, are interlocked with the pantograph air supply.

To open any of these doors, a fouling bar must be raised. The bar closes a safety cock in the pantograph air supply and at the same time opens the pantograph cylinders to atmosphere. The pantographs are thus lowered and the equipment is de-energised when the compartments are entered.

When the doors are closed, the fouling bar must be lowered in order to restore the air supply to the pantograph cylinders.

MECHANICAL PARTS

Underframe and Superstructure

The locomotive underframe consists of four rolled steel channels of deep section well braced with cross members. Buffering and drawgear to the requirements of the Spanish National Railways are mounted at the ends of the underframe.

The superstructure consists of channel members welded together, the whole forming a framework of girder construction which is welded to the locomotive underframe. The superstructure is panelled in steel sheet, the joints of which are continuously welded. The roof is made in the form

of a well, and is removable to facilitate the withdrawal of any of the large items of apparatus mounted within the superstructure.

For operation of the roof isolators and to allow access to the roof generally, a folding ladder is provided immediately adjacent to one of the entrance doors. Immediately this ladder is moved a valve in the air circuit of the pantographs is operated causing the latter to descend.

Bogies

The bogies (Fig. 5) are of the six-wheel bar frame type, braced by cross stretchers of welded construction. The cross stretchers and end members are secured to the frames by turned and driven bolts.

The weight of the locomotive superstructure is transferred to each bogie through a bolster of fabricated construction which carries the bogie centre casting and rests on four nests of laminated springs arranged transversely to the centre-line of the locomotive. These springs are supported on spring planks slung from the bogie frame by means of links. Manganese steel liners are fitted to the rubbing faces between the underframe and centre bolster and also to the thrust faces of the centre bolster recess, through which the tractive forces are transmitted. The locomotive weight is transferred from the bogie frames to the axleboxes through four pairs of coil springs carried on equalising beams, the ends of which rest in slots in the top of the axleboxes which work in manganese steel horn guides. Roller bearing axleboxes are fitted. The transverse movement of the bolster is limited by stops.

This design of bogie combines robust construction with excellent riding qualities and has already been proved in arduous service elsewhere.

The SCOA-P* cast steel wheel centres are pressed on to the axles and the tyres are shrunk on to the wheel centres. The tyres are secured in accordance with the standard practice of the Spanish National Railways.

Air operated sanding gear is provided on all wheels for either direction of running.

Brake Equipment

Vacuum-controlled air brake equipment made by the Westinghouse Brake and Signal Co., Ltd. is fitted on the locomotives, which are equipped for hauling vacuum-braked trains. Service braking is controlled from the driver's vacuum brake valve which operates the vacuum brakes on the train and, through a proportional valve, the air brakes on the locomotive. The air brakes on the locomotive can also be controlled separately by means of a self-lapping driver's brake valve.

Brakes of the double clasp type are fitted, acting on all wheels and giving a brake power equivalent to 85% of the adhesive weight.

Brake rigging details are of steel with pin holes bushed with hard steel. Pins are case-hardened.

Hand brakes are fitted and are operated from a handwheel in each cab, acting on the adjacent bogie.

ELECTRICAL EQUIPMENT

Control Circuit

The driving cabs (Fig. 6) each contain a master controller, brake valves and the necessary switches to control the locomotive while running. The master controller has 4 sets of cams for (a) power notching (b) regenerative braking (c) the reverser and field weakening of the traction motors, and (d) selection of motor grouping for regenerative braking.

Each set of cams is operated by a separate handle. The handles are mechanically interlocked to prevent incorrect operation.

There are 34 power notches of which 9 are 'running notches' (i.e., without resistance in the motor circuits), the latter corresponding to: all six motors in series; two parallel circuits of three motors in series; and three parallel circuits of two motors in series. Each of these groupings has two stages of field weakening.

There are 13 regenerative brake notches available in either the parallel or series groupings.

As already mentioned, the air brakes and vacuum brakes are interlocked with each other so that when a normal vacuum application is made on the train, a proportional air brake application is made on the locomotive. In the event of an emergency brake application, regenerative braking is automatically cut out.

The contactors and cam-operated switches used

* *A design of wheel first introduced by the Steel Company of Australia.*

Fig. 6. Driver's controls

to control the motor speeds and groupings in this equipment are operated by compressed air. The air is admitted to or released from the operating cylinders of the contactors by electrically operated valves under the control of the master controller or of auxiliary contacts mounted on certain items of equipment.

Auxiliary contacts ensure that all switching operations are carried out in correct sequence, by controlling the actuating circuits of the contactors and cam switches in conjunction with the controller.

Although the controller initiates operations, they can only reach completion after every item of apparatus has functioned in correct sequence or if the position of all associated apparatus is correct.

In addition to the air operated apparatus there are electro-magnetic contactors and relays. Some of these are controlled by push buttons in the driving cabs, some by the controller and some by auxiliary contacts on other apparatus.

The control supply is derived from No. 2 motor-generator set working in conjunction with a battery.

The locomotives are arranged for multiple unit operation so that two locomotives coupled together can be operated from any one driving position.

The contactors, group switches and reversers are mounted in steel cubicles.

The starting resistances are of the edgewise-wound type mounted on heat-resisting ceramic insulators, the units being supported on steel rods and the assemblies housed in steel supporting frames.

Power Circuit

Motoring

During motoring the current passes via the pantograph isolating links and the main isolating switch to the main overload relay, the line-breakers, contactors and resistance network, through the traction motors and thence to rail. The grouping of the motors is shown in simplified form in Fig. 7.

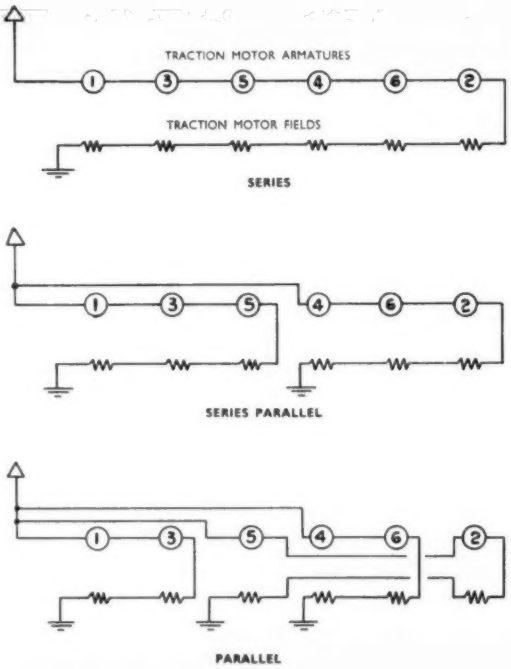


Fig. 7. Simplified diagram of motoring connections

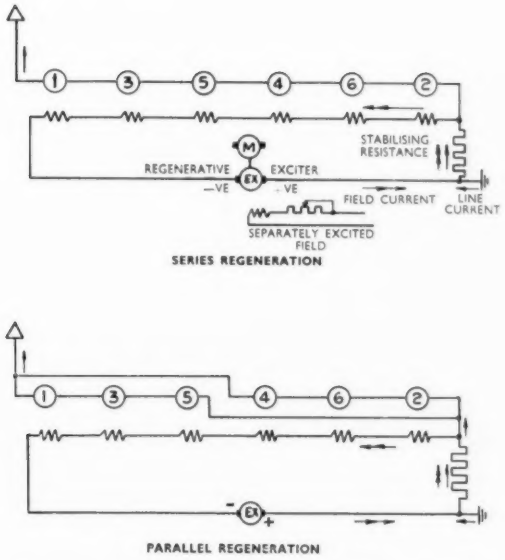


Fig. 8. *Diagrammatic representation of regenerative braking circuits*

At starting, the motors are connected all in series and the steps of starting resistance, also in series, are progressively cut out as the controller is notched up. For higher speeds the motors are connected in two parallel groups of three motors in series, the starting resistance being reinserted and again progressively cut out. For the highest speeds the motors are connected in three parallel groups of two motors in series and the starting resistance is again reinserted and progressively cut out.

For each motor grouping, after the resistance has been cut out, two higher speeds can be obtained by shunting portions of the traction motor fields.

The transition from one motor grouping to another is carried out by the shunt method, which allows the necessary changes to be made without removing power from the locomotive.

Regenerative Braking

Regenerative braking is provided so that the kinetic energy of the train can be returned to the overhead conducting wire. Braking is obtained by converting the traction motors into generators. A representation of the regenerative circuits is given in diagrammatic form in Fig. 8.

The armatures of the traction motors are connected in series (or series-parallel) whilst the fields of the traction motors, being all connected in series, are separately excited by current derived from the regenerative motor-exciter set.

The field circuit of the exciter is variable, enabling a variable current to be passed through the traction motor fields, thereby determining the amount of regeneration.

The regenerative brake is intended primarily for use on long down-grades. As will be noted, there are two motor groupings, series or parallel. The grouping to be adopted depends on the speed of the train at the commencement of braking, the series grouping being used for the lower speeds and the parallel grouping for the higher speeds.

Traction Motors

The six traction motors are of the force-ventilated axle-hung nose-suspended type driving the axles through single reduction spur gears. The one-hour rating of each motor is 600 h.p. and the continuous rating 500 h.p. with a line voltage of 3,000 volts, these ratings being in accordance with B.S. 173 for Class B insulation.

Each motor is fitted with grease lubricated roller armature bearings and sleeve suspension bearings, the latter being oil and cotton-waste lubricated.

Former-wound bakelised armature coils are used. The field coils are machine-wound, the complete coils being vacuum impregnated in synthetic high-temperature varnish and baked.

The final drive gearing is enclosed in a welded sheet-steel split gearcase which is supported from the motor frame. The pinion is shrunk and keyed on to the motor shaft, and the gear-wheel pressed on to the axle. A special feature in the design of the gear-wheel is that it allows a certain amount of torsional resilience between the motor armature and the axle, thereby reducing the transmission of road impact shocks to the armature.

Pantographs

Current is collected by two double-pan pantographs which are air operated and spring controlled.

The design of the pans conforms to the standard practice of the Spanish National Railways.

Auxiliary Machines

The two motor-generator-blower sets each consist of a 3,000-volt motor driving a generator and a rotary fan. The generators provide power at 110 volts for the auxiliary circuits, regenerative braking and battery charging. Each fan supplies cooling air to three traction motors.

Two motor-driven air compressors supply compressed air for the control apparatus and operation of the locomotive brakes. Two motor-driven exhausters of large capacity are used for the operation of the train brakes. The motors of the compressors and exhausters run from the low-voltage supply.

In an emergency the lead-acid battery provides for the operation of one exhauster.

Thrust Bearings for Vertical Shaft Water Turbine Driven Generators

By J. B. YOUNG, B.Sc., Dipl.R.T.C., A.M.I.E.E., Chief A.C. Engineer, Machine Design Department.

PROBABLY THE MOST important part of a vertical shaft alternator is the thrust bearing, as it has to carry the hydraulic thrust in addition to the weight of the rotating parts of the turbine and alternator, and must operate satisfactorily under all conditions of load and at all speeds up to maximum runaway speed. In some cases the hydraulic thrust is appreciably greater than the weight of the rotating parts, and total bearing loads of the order of 1,000 tons have to be considered.

Practically all thrust bearings are similar in principle in that one or other of the bearing surfaces is divided into a number of segmental pads so supported that when rotation begins a wedge shaped oil film is formed between the surface of each pad and that of the other member. Due to its viscosity, oil in contact with the rotating thrust face is dragged circumferentially to form an oil film between the rotating and stationary surfaces. It will be appreciated therefore that oil entry is confined to the radial 'leading' edge of the pad but the 'trapped' oil forming the oil film does not all continue circumferentially to leave by the radial 'trailing' edge of the pad, part escaping across both the outer and inner circumferential boundaries of the pads due to the film pressure, the average value of which is normally of the order of 400 p.s.i. The foregoing, combined with the increasing velocity of the oil as it traverses the pad, results in a thinner film at the trailing edge than at entry. This explanation may be of assistance in visualising the wedge action.

Although the wedge principle is common to all thrust bearings the method of supporting the pads varies with different designs, the most common variations being to provide under each pad a single point pivot, a radial line pivot, a spherical seating, a flexible disc or a mattress of springs. In each case the normal practice is to have babbitted pads. A further variation is used on the Continent where the thrust pads are of cast iron without babbitt and integral with the support ring like a series of cobbler's lasts, a slender neck between each pad and the support ring allowing the pads to tilt. Theoretically, since the load is carried on the oil film, babbitt is unnecessary so long as the oil film is maintained. If a high spot develops and breaks through the oil film on a white-metal lined pad, the heat set up can cause the metal to run locally and relieve the high spot, but with an unlined pad any local heating results in thermal expansion of the metal

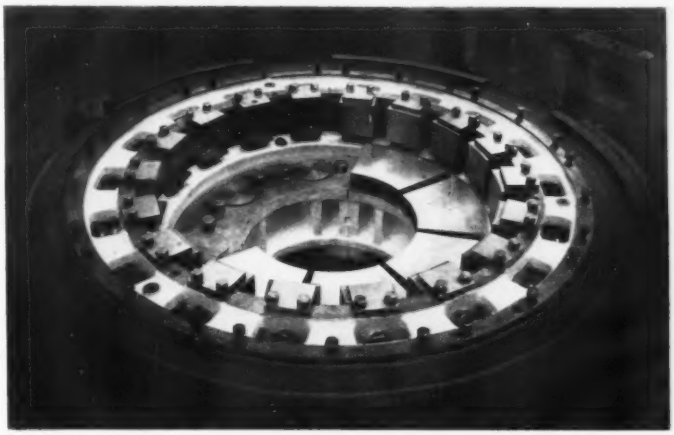


Fig. 1.—An early type of thrust bearing

which aggravates the rub, so giving a cumulative effect which might easily result in cracking of the rotating bearing surface and a costly repair.

The following notes on the evolution and development of The English Electric Company's present bearing based on operational experience may be of interest.

An Early Bearing

Fig. 1 shows the combined thrust and guide bearing used in the early 'thirties.' The rotating bearing surface is carried on the babbitted surfaces of a number of thrust pads each of which rests on a steel disc which, in turn, is pivoted on a dome-shaped hardened steel insert fitted into the top of the pad adjusting screw. Individual vertical adjustment is thus provided for each pad, the pads being free to tilt in any direction but constrained from lateral movement by means of dowels projecting from the thrust support ring in which the pad adjusting screws are housed. In order to facilitate oil entry the leading edge of each pad is relieved slightly, and the fact that the pivot point is offset circumferentially towards the trailing edge gives a slight downward bias to the leading edge of the pads due to the unbalanced weight.

In this design the thrust support ring rested solidly on keys recessed into the wall of the oil chamber, and reliance was placed in varying deflections of the radial arms supporting the oil chamber to give some measure of flexibility. This arrangement had disadvantages in that it was necessary to lower the thrust bearing assembly to carry out an examination of the thrust pads, as shown in Fig. 2. In order to permit such dismantling, part of the base of the oil pot and the whole of the inner wall of the thrust oil pot had to be split diametrically and oil-tight joints remade on reassembly.

The first alternators manufactured with the bearing shown in Fig. 1 were of the umbrella type and ran satisfactorily for several years. The rotating thrust face was detachable and was therefore split diametrically for assembly, as the shaft had a forged flange at each end. The two halves of the thrust face were bolted together and then spigoted and dowelled to the upper shaft flange. After several years of trouble-free running, traces of rust in the oil disclosed that slight movement was taking place between the detachable collar and the shaft flange, giving rise to fretting corrosion. The trouble was overcome by bolting the detachable

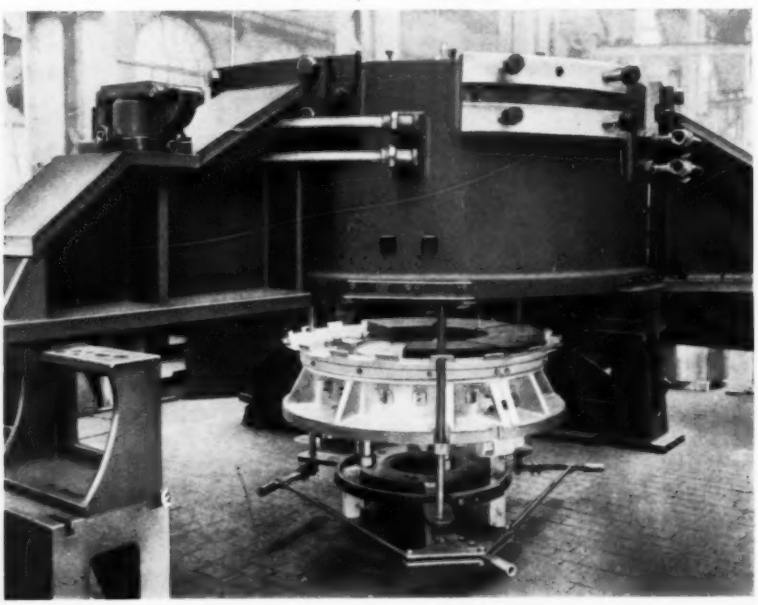


Fig. 2.—A thrust bearing as lowered for examination

thrust face securely to the shaft flange in addition to the dowels and spigot.

Arising from this experience the logical step was to dispense with the detachable thrust collar and make the rotating thrust face integral with the shaft. An undesirable feature of a split thrust face is that any relieving of the radial joints at the split results in a pulsating pressure on each pad twice per revolution.

The thrust face integral with the shaft has been this Company's standard practice on umbrella type alternators for the past 9 years and has given very good results.

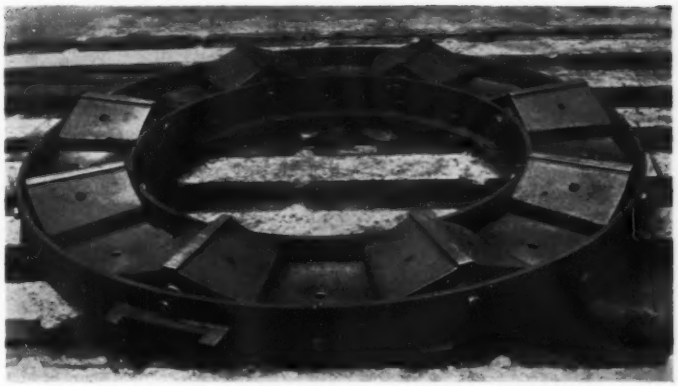


Fig. 3.—Equalising ring

Flexible Mounting

In investigating the reason for the earlier fretting corrosion it was realised that some additional flexibility in the mounting was desirable to compensate for any slight deviation from normality of the thrust face to the axis of the shaft. An equalising ring (Fig. 3) has therefore been included between the thrust bearing support ring and the base of the oil pot. This consists of a series of levers which permit the thrust pad support ring to ' breathe ' and so maintain uniform pad loading even though the plane of the rotating thrust face is not quite perpendicular to the axis of rotation.

The operation of the equalising ring will be clear from a study of Fig. 4. Assume some out-of-truth or misalignment which necessitates a reduction in the depth of the self-aligning equaliser at A. L and C must depress ; pad 3 pivots about M depressing K, and pad 2 pivots about J uplifting H. As C is depressed, pad 5 pivots about B depressing D, and pad 6 pivots about E uplifting F. Since pad 1 sits on F and H, G is raised. A and G are diametrically opposite, the depth at A being reduced and that at G increased.

The equaliser thus performs the same function as a spherical seating and has the advantage that it is easier to manufacture. In its simplest form, viz. a 4-pad equaliser, the operation can be demonstrated by crossing two pencils on a table and tilting in any direction a disc placed on top. Fig. 5 shows a bearing assembly designed for a total load of 750 tons, with the equaliser in position.

Access

In order to avoid lowering the bearing assembly for pad inspection other access methods were considered. For the past 8 years this Company's standard practice has been to provide doors in the vertical outer wall of the thrust bearing oil pot, a door being located between each bracket arm through which the thrust pads can be withdrawn without altering the adjustment of individual pads. Fig. 6 shows the supporting bracket and oil pot

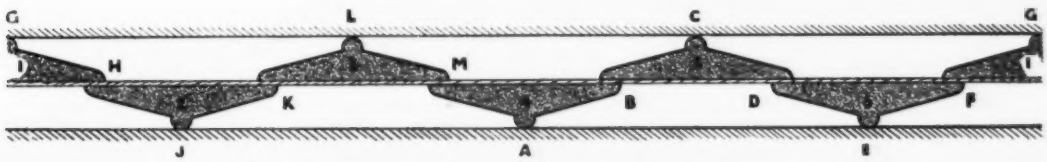


Fig. 4.—Diagrammatic representation of a 6-pad equaliser

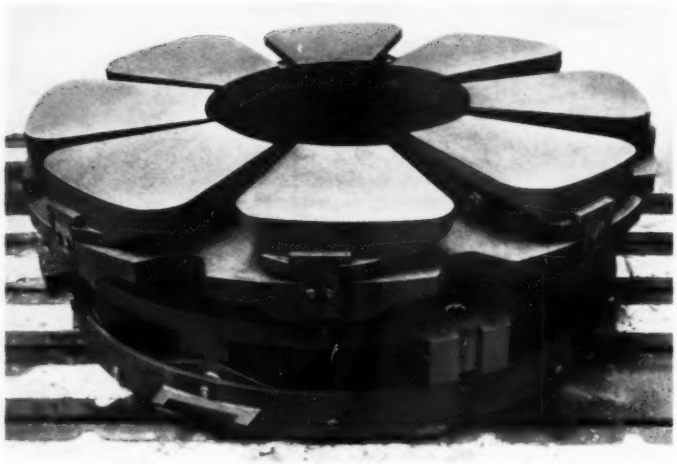


Fig. 5.—Bearing assembly for a total load of 750 tons

with access doors for a bearing capable of carrying a load of 750 tons at a normal speed of 150 r.p.m. and up to 367 r.p.m. at runaway. Where necessary because of weight considerations rollers are provided so that the pads can be rolled down rails to a position where they can be more conveniently handled by a pulley block. The rollers can be seen in Fig. 5.

Lubrication

In the earlier bearings cooling coils were immersed in the oil pot to extract the heat equivalent of the bearing friction loss, and were quite effective, but as bearing sizes increased with correspondingly higher friction losses, experience showed that more positive cooling was desirable. A convenient method is to have a sump capable of housing all the oil in the system, from which oil can be pumped through an oil cooler. A supply of cool oil can thus be assured where it is required, in the region of the inlet to the thrust pads, the oil level being maintained in the thrust oil pot by means of weirs. Such an arrangement is ideal from the point of view of maintenance as it is only necessary to open a normally locked valve to drain the oil pot, after which pads can be withdrawn for inspection through the access doors. A minimum of dismantling is necessary, and after examination the pads and doors can be replaced and the oil level restored ready for running in an extremely short time.

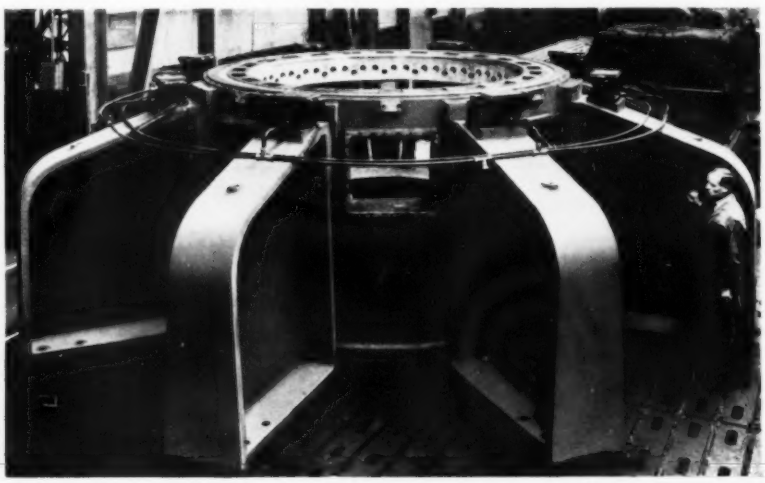


Fig. 6.—Lower bracket and thrust bearing oil pot for 750 tons load

The finish of the bearing surface is important, and experience has shown that a thrust face hand-scraped to a surface plate operates at least as well as one with a mirror finish. The shallow cavities due to the scraping of the pads and the rotating thrust surface act as tiny oil reservoirs between the mating surfaces and help to establish an oil film quickly even after a lengthy shut-down period.

Conclusion

The secret of a successful bearing lies in the provision of an adequate supply of cooled oil to a good bearing surface and, above all, a flexible mounting for the bearing support ring which will enable the pads to accommodate themselves at all times to the plane of the rotating thrust face even if it is not perfectly normal to the axis of rotation.

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Some Recent British Cotton Mill Electrifications

By J. G. WINTERBOTTOM, Assoc. I.E.E., Assoc. A.I.E.E., Chief Engineer, Textile Division, and J. C. EDMED, D.F.H., A.M.I.E.E., Textile Division.

DURING THE PAST 150 years the British cotton industry has played a leading part in the world's production of yarn and fabrics. The first textile machines were manufactured in this country, by pioneers such as Crompton, Arkwright, Hargreaves and others. At the close of the first world war Lancashire stood supreme as the largest exporter of cotton goods in the world, and also as the main manufacturing area for cotton spinning and weaving machinery.

After the last war Britain's economic position made it imperative for the cotton industry to produce more for export, and some mills which were closed during those war years were re-opened, and many others modernised, to meet the increased demand. In several factories the machinery was

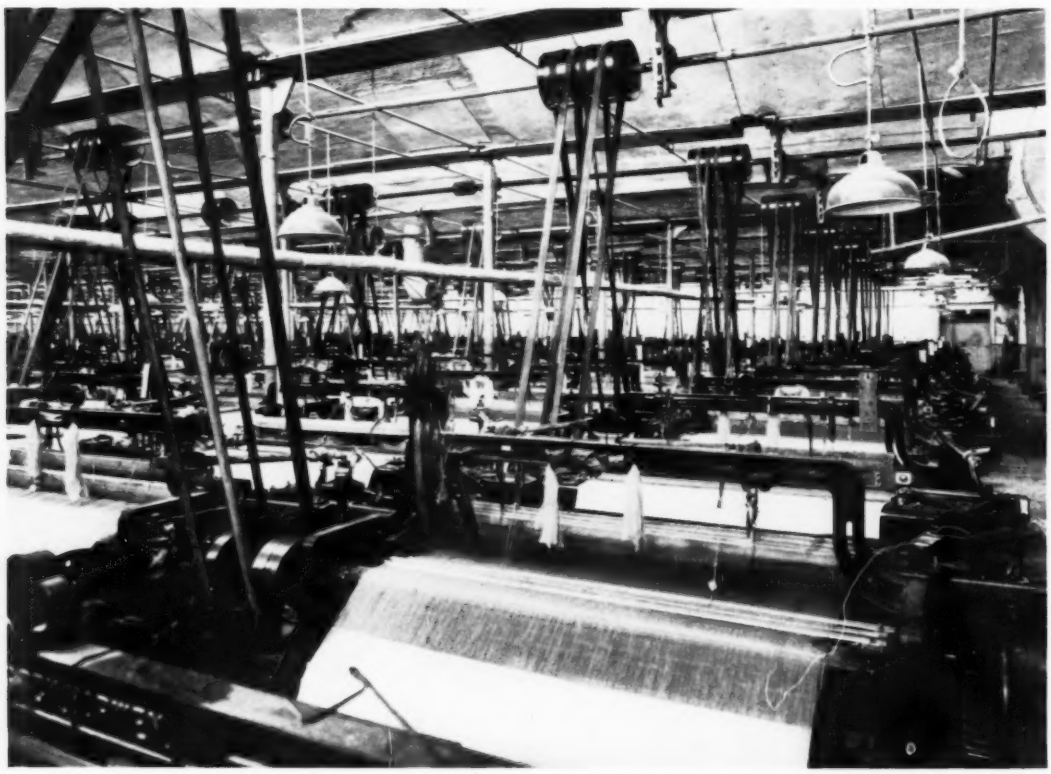


Fig. 1.—*An old weaving shed with machines driven by leather belts from overhead lineshafts*

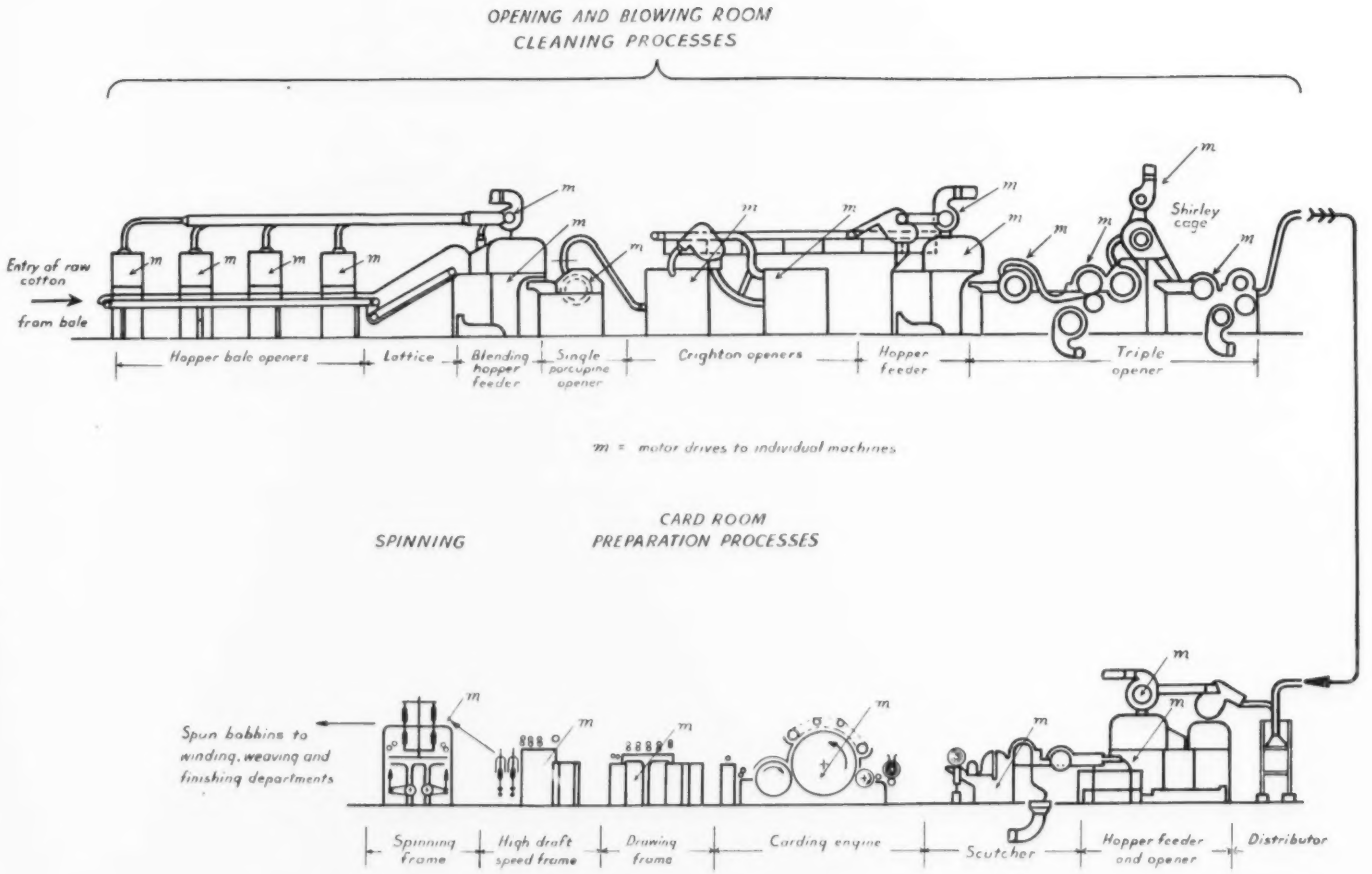


Fig. 2.—Typical range of machines used in cleaning and preparing raw cotton for spinning

rearranged and labour redeployed, and in some cases new plant was purchased with a view to increasing production. The majority of the cotton mills however are still driven by steam engines, involving overhead lineshafting with steep belt drives to the respective machines, and improvements in production are frequently limited by this form of driving (Fig. 1).

In recent years there has been a steadily increasing trend towards electrification of textile factories, brought about partly by the re-spacing of machines and also because of the condition of existing old engines and boiler plant.

A conversion from steam to electric drives involves many problems. Every mill has peculiar features such as the construction of its buildings, the dispositions of the different mill departments and machinery, and the layout of lineshafts. Many old factories have their machines packed closely within a small floor area, with consequent restriction of the space available for modifying the machinery to take individual motor drives. In mills where group electric drives are advisable it is often necessary to make important modifications to the lineshafts and structural alterations to the mill building to accommodate the large motors required.

Before an electrification scheme can be drawn up, the mill must be carefully surveyed and inventories made of the machinery installed. The scheme must then be treated comprehensively so as to provide the most economic proposition, and must be so planned as to avoid any loss of production during the changeover by ensuring the continuous running of the machinery.

This article describes some typical cotton mill electrical installations which have recently been undertaken by The English Electric Company, but before doing so the following brief explanation of the processes involved in the production of cotton yarns and fabrics may be of interest to those not familiar with this subject.

Processes in a Cotton Mill

The manufacture of woven cotton cloth falls naturally into five distinct stages :—

1. Cleaning the raw cotton, including the opening stages.
2. Preparation, including carding, combing, drawing, and roving on high draft speed frames.
3. Spinning, doubling, winding and warping.
4. Weaving.
5. Finishing, including dyeing, bleaching and printing.

Raw cotton is imported from such sources as the cotton fields of the Americas, Egypt and the British Colonies. It is despatched to the mills in compressed bales, each containing a specific ' staple ' or fibre length and growth, and it is often necessary to mix two or more grades in order to provide the desired type of raw material for processing.

The cleaning of the raw cotton is of vital importance, and for this purpose it is treated in a range of machines typically as shown in Fig. 2. It is usual to place the contents of the bales of different growths into separate hopper bale openers. Each of these handles one specific class of cotton and, after a loosening treatment, automatically discharges the requisite amount to the blending hopper feeder, where it is beaten by spiked rollers and considerable dirt is ejected.

The cotton is then passed through a system of further opening machines such as the porcupine opener, crighton opener, triple or double opener, hopper feeders and scutchers. Each of these machines has high-speed revolving drums or beaters with spikes or blades which further open the particles of cotton and remove impurities still existing. The cotton, which at this stage has the appearance of snowflakes, is drawn through these machines by the suction provided by a system of powerful fans.

Finally, at the scutcher or last stage of cleaning, the flakes of cotton are deposited to form a flat strip of material resembling a loose fluffy blanket, and this is coiled into a roll about 40 inches wide at the delivery end of the machine. It is common practice to take three or four of these rolls, or laps as they are called, and set them up in a further scutcher, feeding the several layers through the beater, from which they emerge as one lap having a density corresponding to the number of laps combined.

Although the raw cotton has been thoroughly cleaned during the opening processes, the material is in a tangled state, with the cotton fibres in the laps pointing in all directions. Before the cotton can be spun it is therefore necessary to sort out and ' parallelise ' the fibres by a process known as ' carding '. This is often regarded as the most important operation prior to spinning, and consists in effect of combing and fibre-straightening. A carding engine into which the cotton is fed for this purpose comprises three rotating cylinders covered with small steel-wire bristles. The cotton is delivered from the carding engine in the form of ' ropes ' or ' slivers ' of about 1 inch diameter which are coiled into tall cylindrical rotating cans.

Groups of slivers are either subjected to further combing to eliminate all short fibres, or are fed into drawing frames which draw and stretch them, combining them into a single sliver. A drawing frame comprises a number of pairs of fluted rollers (drafting rollers), each pair pressed together by weights and rotating at a different speed. The delivery is fed into cylindrical cans similar to those used with the carding engine.

The degree of combing imparted to the raw material is determined by the quality of cotton processed. Long staple cotton used in the production of fine yarns and fabrics requires more combing and drawing to remove any further irregularities in the slivers.

The next operation is to reduce the diameter of the sliver to a fine ' roving ' or cord which is suitable for spinning into a thread. The high draft speed frame stretches the sliver considerably and performs in one operation the work that formerly needed two or three individual machines. After leaving the drafting rollers of this frame, the roving is wound on to bobbins by means of a fork or ' flyer ' provided with a thread-guide to ensure even distribution on the bobbin and to control the tension of the roving as the diameter on the bobbin increases. The bobbins when full are removed and placed in the spinning frames preparatory to spinning.

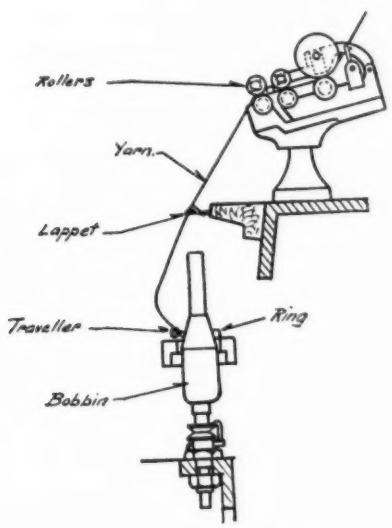


Fig. 3.—Diagram of ring spinning frame, showing path of yarn from rollers to bobbin

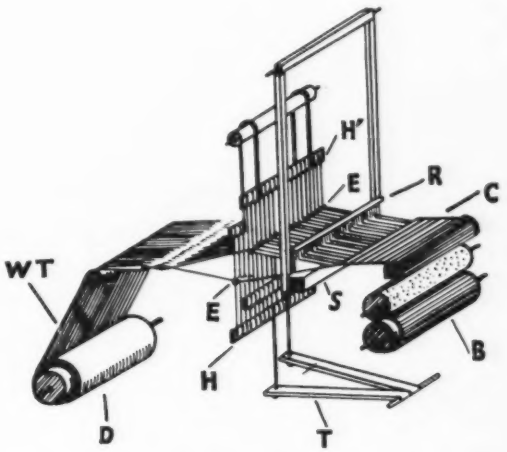


Fig. 4.—Diagrammatic arrangement of a hand loom

(With acknowledgements to " Textile Electrification " by Wilhelm Stiel, published by George Routledge and Son Ltd.)

The description of spinning in this article is confined to ring spinning frames which are now used almost universally for spinning cotton, although ' mule ' spinning is still employed for very fine yarns. The ring frame is simple in construction and consists of some 300 to 400 stationary steel rings each surrounding a bobbin,

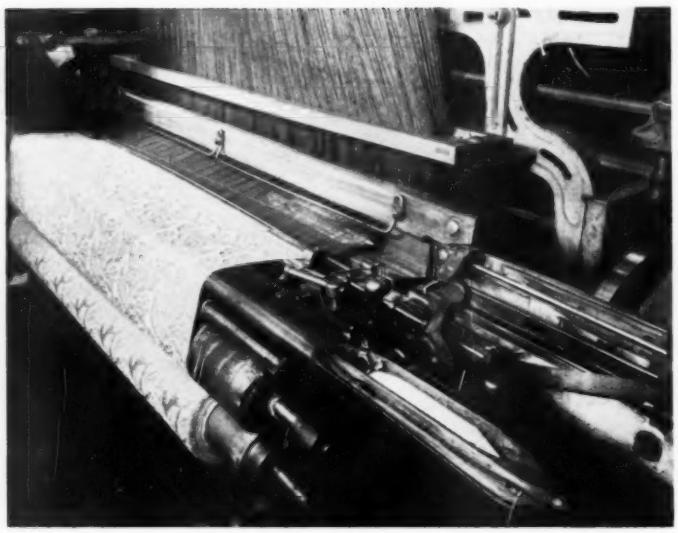


Fig. 5.—A power loom weaving casement material. The shuttle is between the warps, and the weft is moving back to the cloth

threads (warp) are interlaced in pre-arranged fashion with a crosswise thread (weft) which is guided to and fro in a shuttle. Fig. 4 shows in diagrammatic form the arrangement of a hand loom. The warp threads WT are carried on a drum D and taken through the thread guides or eyes E. The eyes are carried on ' healds ' H and H' which may be moved in a vertical plane by means of the treadles T. From the eyes the threads are taken through separating wires or reeds R located on the sley S which may be moved in a horizontal plane. Alternate warp threads are drawn apart by the movement of the healds, a weft yarn is propelled by means of a shuttle along the sley between the warp threads, the sley is moved forward and the warp threads rearranged by changing over the positions of the healds ; the cycle of

as shown in Fig. 3. These rings are highly polished and each is provided with a bevelled edge or lip to which is clipped a small hook or ' traveller ' free to travel round its periphery. The rings are located along two rails, one on each side of the ring frame, the rails extending the full length of the machine and moving in a vertical plane. The roving is fed through a series of drafting rollers and is threaded through the traveller to the bobbin below. As the bobbin and drafting rollers rotate, the ring traveller acts as a drag imparting twist to the yarn as it winds on to the bobbin, whilst the vertical movement of the ring rail enables the yarn to be evenly distributed on the bobbin.

The yarn is next prepared for weaving, which consists of combining threads to form fabrics. In this process a large number of lengthwise

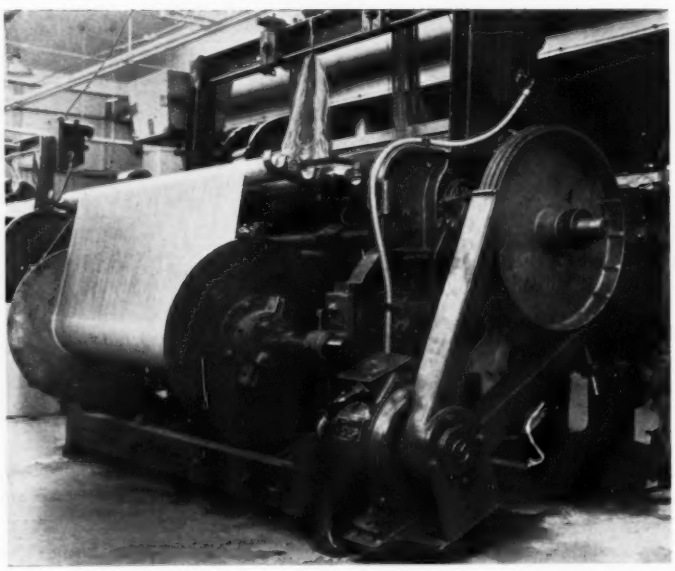


Fig. 6.—Back view of ' Northrop ' automatic loom driven by ' English Electric ' loom motor

Fig. 7.—Lostock Hall spinning mill, near Preston

operations is repeated and a woven cloth C is thus formed which may be wound up on to the cloth beam B.

The conventional power loom is fundamentally the same in principle, with the addition of various devices to fire the shuttle, raise and lower the healds, and drive the sley and beams. Fig. 5 shows a loom weaving casement material, with the shuttle between the warps, and the weft moving back to the cloth. Fig. 6 shows the back of a ' Northrop ' automatic loom driven by an ' English Electric ' loom motor.

There are numerous finishing processes for the cloth, but descriptions of them are beyond the scope of this article.

Lostock Hall Spinning Mill

The Lostock Hall Spinning Company's mill (Fig. 7) was one of the first British textile mills to change over to electric drives after the last war.

It is situated in the country a few miles south of Preston and was built during the latter half of the nineteenth century. The decision to install new ring spinning machinery and associated preparatory plant to replace some of the old equipment involved re-spacing most of the productive plant and, if mechanical drives were retained, the expense of renewing the old lineshafting to suit the new machine positions. Before re-equipment and electrification the mill was driven by a 1,000 h.p. geared steam turbine installed about twenty years previously. The turbine, on the ground floor, drove the respective lineshafts on the different floor levels through manilla ropes in a rope race, as shown in Fig. 8.

It was decided to install individual electric motor units for all the new machinery, and to convert the remaining sections to group electric motor drives for the time being. The English Electric Company was responsible for the complete electrification including the supply of the electrical plant, erection, cabling and millwrighting. The installation work was sub-contracted to Messrs. Edward Dewhurst & Co., Ltd., Preston. The most up-to-date preparation plant was installed, including carding, drawing, slubbing, and roving machinery, together with high draft ring spinning frames, all admirably suited to individual electric motor drives.

The mill electrification was carried out in two stages, the first dealing with the new machinery and the second with the conversions. In the first stage it was imperative to supply electric power to the new machines as erection was completed, so that they could be in production quickly to replace the old machines. As the mill building was divided into two sections, one on either side of the rope race already mentioned, and all the new machinery was to be installed in one section only, it was possible to concentrate on the cabling and electrical

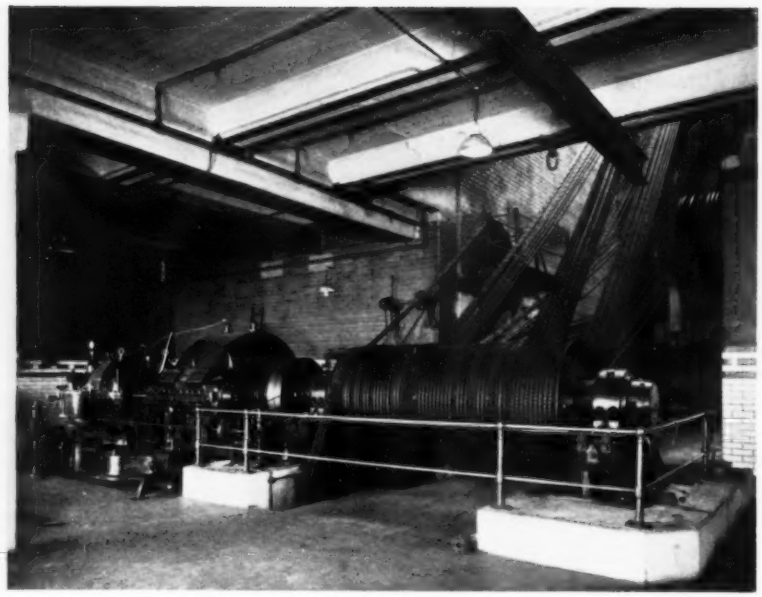


Fig. 8.—The turbine room and rope race

distribution in one part of the building at a time. The load was transferred gradually from the steam turbine to the electric motors, with minimum loss of production.

Prior to electrification the mill obtained only a limited electricity supply for a few auxiliaries and lighting from a small substation near the main mill building. The Supply Authority, then the Lancashire Electric Power Company, extended the substation building and provided for an ultimate transformer capacity of 2,000 kVA. New 11 kV underground feeders were brought into the substation, where the transformers step down to 400 volts. The high-voltage switchgear and transformers were supplied and installed by the Supply Authority, and The English Electric Company was responsible for the supply and installation of all electrical plant on the L.V. side of the transformers.

The L.V. power distribution from the substation fell naturally into two sections corresponding to the first and second stages of electrification in the two parts of the mill.

For the first stage of the changeover, a 2,400 ampere OB 4 type triple-pole air circuit-breaker was installed in the L.V. chamber of the substation. To this breaker was connected the main low-voltage feeder to the main mill building, serving the distribution switchboard for the new machinery drives. The old rope race was selected for the main mill switchroom (Fig. 9) since it was situated at the centre of the building and provided a good vantage point for cabling to the respective departments. This first distribution switchboard, seen against the right hand wall in Fig. 9, consists of an incoming OB 4 type air-break circuit-breaker cubicle with an outgoing busbar chamber on each side fitted with 'Combination' fuse-switch units. The fuse-switches on one side feed all the preparation machinery drives, while all the spinning machinery is connected to the fuse-switches on the other side. Kilowatt-hour meters on the circuit-breaker cubicle record the respective energy consumptions of the preparation and spinning departments. As an additional check, wattmeters are mounted on the fuse-switch units controlling the outgoing circuits. The outgoing 3-core cable-runs to the section boards in the mill departments are mounted on the rope race wall, branching out at the different floor levels. Great care had to be taken when the first switchboard and outgoing

cables were installed since it was necessary to keep the steam turbine and rope drives in operation.

Each department of the mill receives its electricity supply from a local section distribution board comprising an incoming isolating switch and outgoing sub-feeder switch-fuse units which are connected to wall mounted fuse boards. Pyrotenax cables are used for all the circuits between the fuse boards and the motors.

Of the motor drives for the new machinery, all the carding machines are provided with $1\frac{1}{2}$ h.p. 960 r.p.m. high-torque totally-enclosed motors. Short-centre flat belt transmissions are used, the cards having fast and loose pulleys with belt-shifting forks interlocked with the card protecting covers. Special contactor starters are used to provide protection during the severe starting conditions, as a carding engine cylinder constitutes a heavy flywheel load and the acceleration period may be as much as 40-60 seconds, depending on the friction of the machine. Each starter is provided with an interlocked reversing switch to enable the motor to be operated in reverse for the grinding operation of the carding machine.

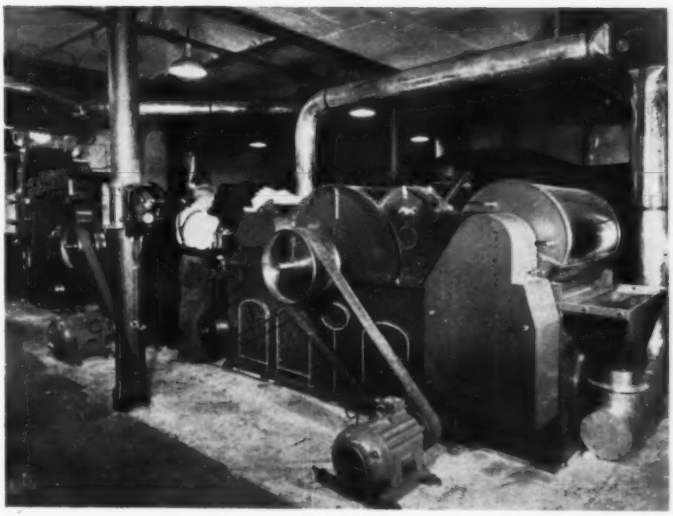


Fig. 10.—Hopper feeder and double cylinder opener driven by 8 h.p. and 4 h.p. 6-pole totally-enclosed fan-cooled motors

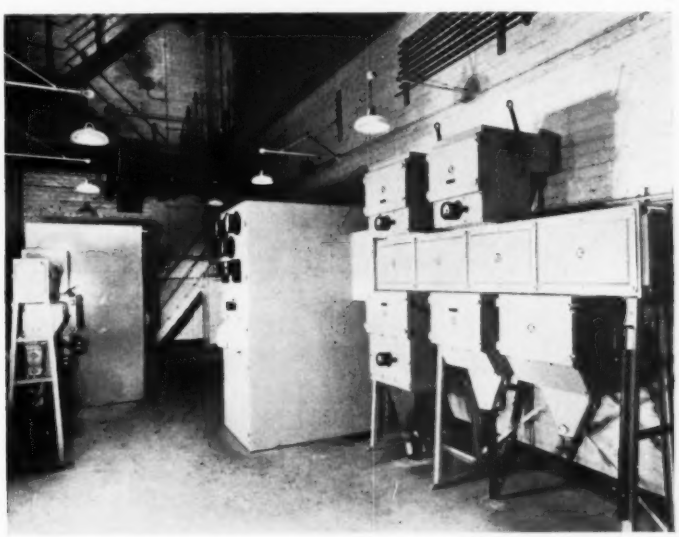


Fig. 9.—Main switchroom, formerly the rope race

Examples of motor drives for the opening machinery, drawing frames and speed frames are shown in Figs. 10, 11, 12 and 13. The spinning motors are of the constant speed smooth acceleration squirrel-cage type, mounted on special combination bedplates fixed to the ends of the spinning frames (Fig. 14). Short-centre vee-belt drives are used, and the motors are controlled remotely by means of pilot limit switches operating in conjunction with the contactor switches.

Following the electrification of the new machinery, the installation in the remaining section of the mill was carried out. A further low voltage air-break circuit-breaker of 1,600 amps capacity was installed in the substation and connected by cables

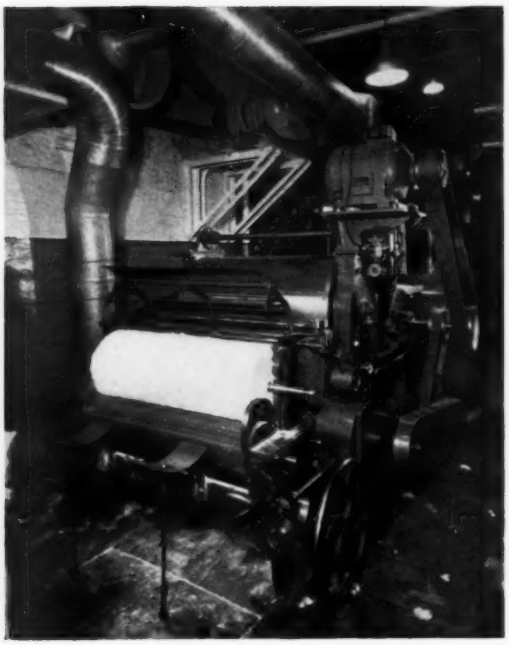


Fig. 11.—*Hopper feeder and single scutcher driven by* 8 *h.p.* 4-*pole totally-enclosed fan-cooled motor*

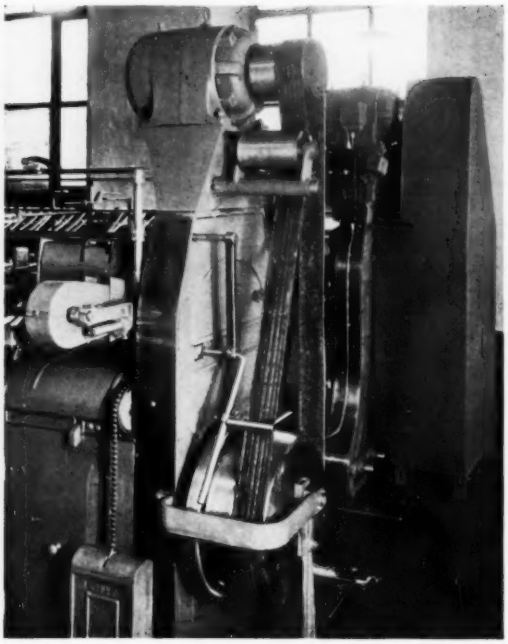


Fig. 12.—*Individual drive to high draft speed frame (with protecting cover removed)*

to a second distribution switchboard in the switch-room of the main mill building. This switchboard is of a similar type to that which was first installed, and is seen on the left of the converted rope race in Fig. 9. Similarly, the cables of the outgoing circuits are carried along the rope race wall and supply the individual drives in the opening and blowing departments, group drives in the old carding department, and the motors in the mule spinning rooms.

The smaller group-drive motors in the opening and carding departments are totally-enclosed wind-cooled, but for certain outputs from 12½ to 55 h.p. they are pipe ventilated machines. All are of the squirrel-cage type controlled by star/delta starters. Arrangements have been made to install individual motor units to drive some of the plant initially group driven.

In the mule spinning departments 100 h.p. group-drive motor units were installed, each motor driving six mule spinning frames. In view of the fluctuating nature of the load, the motor rating had to be carefully selected to give the best spinning conditions with a minimum variation in speed. For this purpose the large manilla-rope pulleys carried by the lineshafts in the rope race were retained to act as flywheels and the motors were mounted in the overlookers' cabins at the respective floor levels. Pipe ventilated slipring motors operating at 950 r.p.m. were used, each connected to the lineshaft by a long-centre vee-belt drive. A series of pilot emergency stop switches was installed at suitable points in the spinning rooms and connected to the respective starters.

Since the main sections of the mill were converted to electric drives, additional plant has been installed including air conditioning in the rooms and cleaner units on the ring frames together with further productive machinery. This has entailed the installation of new motor drives, and the ultimate number of individual drives will exceed 400 machines with an aggregate of over 2,000 h.p.

For power-factor correction two systems were adopted. Initially, condenser banks of 100 kVAr

each were connected to the two main distribution switchboards in the rope race. As additional plant was installed in the spinning rooms, these were supplemented by fitting 3 kVAr condenser units to a number of individual ring frame and cleaner motors. The normal operating power-factor of the mill is by these means corrected to 0.92-0.95 lagging, and the individual condenser units have the added advantage of reducing the reactive currents in the intermediate feeder cables.

Fieldhouse Mills, Rochdale

Since the last war, Messrs. John Bright & Brothers have re-equipped and modernised their mills in Rochdale. Following the installation in their Fieldhouse Mills of new spinning frames for the production of coarse cottons used in the manufacture of tyre fabric and conveyor belting, it was necessary to re-space much of the plant. In 1949 The English Electric Company, in co-operation with the Rochdale Electric Company, undertook the electrification of the preparation and carding departments, involving the installation of over 200 individual motor drives ; some examples of these are shown in Figs. 15 to 18.

Fig. 14.—*Part of an installation of individual motor drives to ring spinning frames*

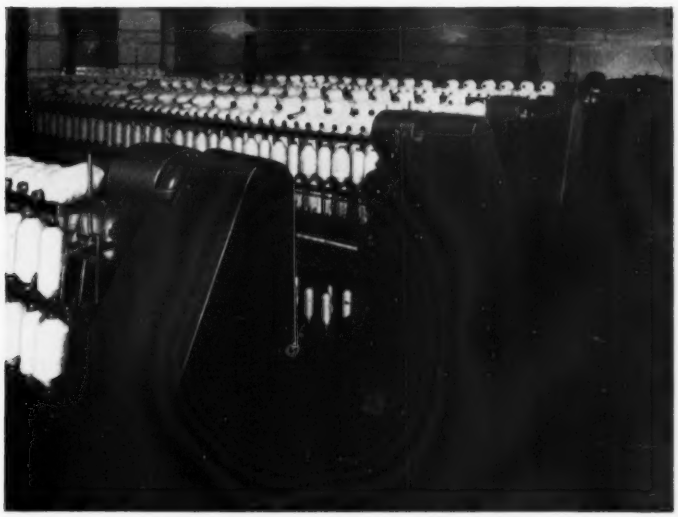


Fig. 13.—*Speed frames driven by individual motors*

The principal problem was to maintain production throughout the changeover of the machinery from lineshaft to individual motor drives. The carding engines (Figs. 16 and 17) were of an old design provided with fast and loose pulleys connected by flat belts to the overhead lineshafting. To retain the essential driving features it was necessary to build the motors inside the machines and to use special clutch pulleys, grooved for taking vee-belts, to replace the fast and loose flat belt

Fig. 15.—*Scutcher with individual motor drive, as seen from the feeding end with cotton laps set up and belt guard removed*

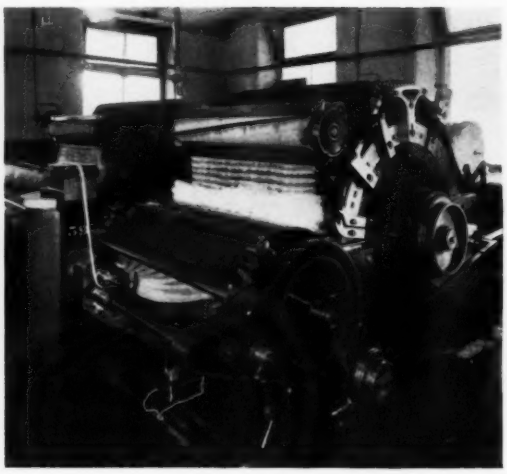


Fig. 17.—*Individual drive to carding engine, showing the new clutch pulley driven through vee-ropes (in protecting cover) by a motor in the base of the machine (extreme right)*

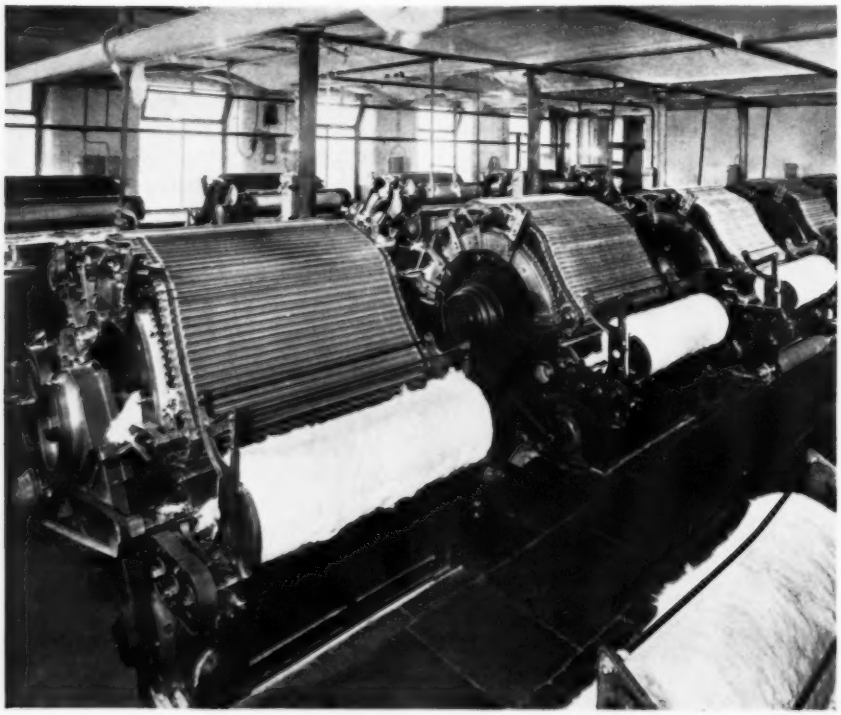


Fig. 16.—*Carding engines converted from overhead lineshaft to individual motor drives*

Fig. 18.—Draw frames converted from lineshaft to individual motor drives

pulleys. Prototype drives were designed in conjunction with Messrs. John Bright and Brothers and their millwrights, and then thoroughly tested under actual operating conditions, before producing in quantity the driving transmissions for all the carding departments. It is often necessary to adopt this practice in the conversion of old machinery, since millwrighting expenditure constitutes a high proportion of the total electrification costs.

A centrally sited substation had already been established by Messrs. John Bright and Brothers to feed other sections of the mill, but it was necessary to extend the existing L.V. switchboard and to sectionalise the outgoing feeder loads. The switchboard extension was built in two sections comprising OB 3 type air-break circuit-breakers for the duplicate L.V. feeders from the transformers, a bus section switch and outgoing ' Combination ' fuse-switch units.

As the walls of the mill buildings were very thick, a careful choice of cable routes to the several floors was necessary to minimise structural alterations.

Individual Drives to Cotton Looms

Among the weaving sheds recently powered by individual loom-motor drives, that in the School Lane Mills of Messrs. A. & S. Orr at Bamber Bridge is a notable example. This shed was rebuilt soon after the war, and new ' British Northrop ' looms equipped with ' English Electric ' loom motors were installed. Fig. 19 shows the improved operating conditions compared with a typical old lineshaft-driven shed as in Fig. 1. Individual motor drives in a spinning room of the same mills are shown in Fig. 20.

The mechanical complexity of a loom and the nature of the weaving process necessitate special features in the electric drives. The continually fluctuating load and severe starting conditions call for specially designed high-torque motors. The starting torque must be sufficient to ensure rapid acceleration of the loom from rest up to full speed, as the first pick (first shot of the shuttle) should be made at the same speed as subsequent picks if faulty material is to be avoided. This requires a motor capable of exerting at least 2½ to 3½ times the normal full-load torque during the starting period.

Looms start and stop many times a day, and in order to compensate for the heat generated in a motor by repeated starting, the motor is designed

for a low temperature rise which in general never exceeds 35°C. by thermometer above the surrounding atmosphere after a full-load run of six hours.

The flexibility of the electrical drive for textile machinery is now widely appreciated, and the individual drive has been adopted generally where existing lineshafting is in poor condition, or where spacing of machinery has made it necessary. The individual drive also has the advantage over the older method of electrical group drive of reducing machinery stoppages to a minimum, as a small motor can quickly be replaced.

It has been proved during recent years that the friction loads due to lineshaft bearings and heavy cotton rope or leather belt transmissions in engine-driven factories can range from 10% to 25% of the total engine indicated horse-power. The individual electric drive of machinery eliminates most of this power loss. It also ensures that each machine is driven at the correct production speed, whereas in flat-belt lineshaft drives there is a considerable loss due to belt slippage.

Recent power investigations in some Lancashire mills have shown that the running cost of a prop-

Fig. 19.—*Weaving shed equipped with automatic looms of the latest design, driven by individual loom motors*

Fig. 20.—*New ring spinning frames with individual motor drives*

erly designed all-electric factory is now no more, and in some cases less, than that with the old steam engine drives. The considerable rise in the cost of coal to industry during the past few years will naturally also influence the future use of electrical drives to a greater degree.

Acknowledgements

The authors appreciate the permission of the following firms to describe and illustrate their premises and plant in this article :—

The Lostock Hall Spinning Company Limited, near Preston. Chief Engineer, Mr. W. Wadsworth.

Messrs. John Bright & Brothers Limited, Rochdale.

Messrs. A. & S. Orr Limited, Preston.

The Use of Quadrature Booster Transformers in Power Systems

By S. E. NEWMAN, A.C.G.I., A.M.I.E.E., and W. P. WILLIAMS, A.H-W.C., Grad.I.E.E.,
Switchgear Engineers' Department.

FOR THE EFFICIENT operation of any interconnected electric power system it must be possible to control the flow of power through the separate branches of the network. Load demands for both active and reactive power have to be supplied by the power stations and transmitted along the lines, and in a complex system it is unlikely that the natural division of flow between the various lines will be the best from the points of view of economics, equipment rating or operational requirements. Hence means must be provided to direct the active and reactive power in a network up certain lines and vary the division at will as the system conditions vary. In this article the principles and use of quadrature booster transformers for this purpose are described.

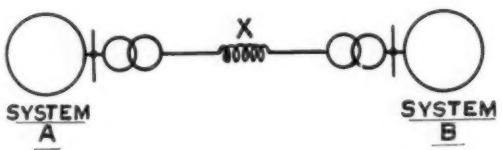


Fig. 1. A single transmission line connecting two power systems

Single Interconnectors

In Fig. 1 two power systems A and B are represented. Both are a combination of generator units and loads and are connected by a single transmission line of reactance X. The transfer of power between these two systems is easily achieved. If the load requirements of active power in System B exceed its available generating capacity, surplus power may be imported from System A by altering the prime mover governor settings of the generating units in A and so increasing their output. The phase of the voltage at the A terminal busbar then moves in advance of that at B and power is transmitted through the line.

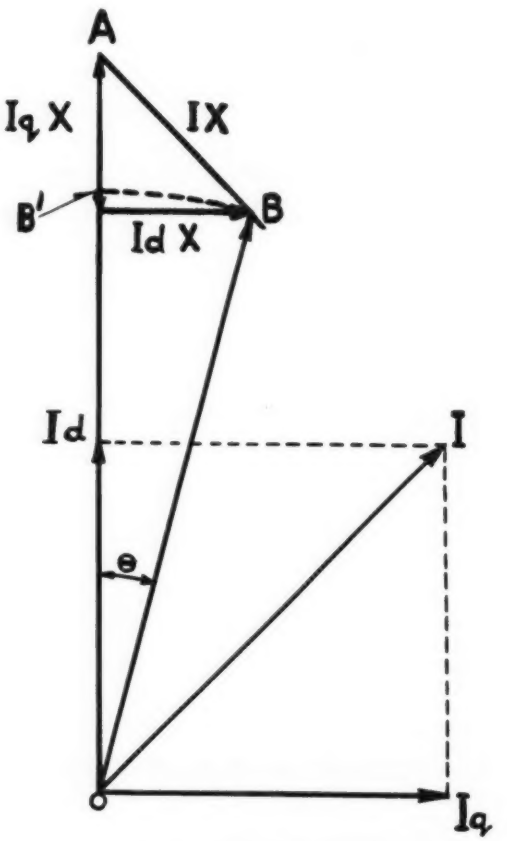


Fig. 2. Vector diagram for the single interconnector shown in Fig. 1, with resistance neglected

It is not necessary to increase the voltage to

obtain a transfer of active power. If the flow of reactive power between the two systems is to be altered, however, then the relative voltages at the ends of the line must be varied. Considering the flow of power in terms of megawatts (MW) and megavars (MVAr) ; with a given number of MW flowing from A to B at a lagging power factor it is convenient to consider that lagging MVAr are flowing in the same direction. In such circumstances an increase in the voltage at the A terminal busbar would be accompanied by an increase in the flow of lagging MVAr towards B, *i.e.* the power factor would become lower.

A simplified vector diagram for the single interconnector of Fig. 1 is given in Fig. 2. Here the vectors AO and BO represent the voltages at the line terminals of the systems A and B respectively. AB represents the vectorial difference between these two voltages or the driving voltage required to transmit the power down the line. The difference in magnitude between the terminal voltages is given by the length AB′, and it is this value (the arithmetic difference) which when added to any no-load rise due to the line capacitance gives the voltage regulation. The angle θ is the phase angle between the terminal voltages. The direct and quadrature components of the line current I with respect to the voltage AO are shown as Id and Iq, and these are proportional respectively to the active and reactive power exported from System A. It will be noticed that the voltage drop due to the quadrature component (IqX) is in phase with AO, whereas the voltage drop due to the direct component (IdX) is in quadrature with AO. Put in terms of driving voltages, the component of the driving voltage in phase with AO transmits reactive power whilst the quadrature component transmits the active power. These two factors are not entirely independent in practice due to the presence of resistance which in this instance has been neglected.

Thus, with a single interconnector between two power systems, the power in the line may be completely controlled by altering the prime mover governor settings and the generator excitation. In practice, in the case illustrated, the reactive power would probably be controlled by changing the transformer ratio.

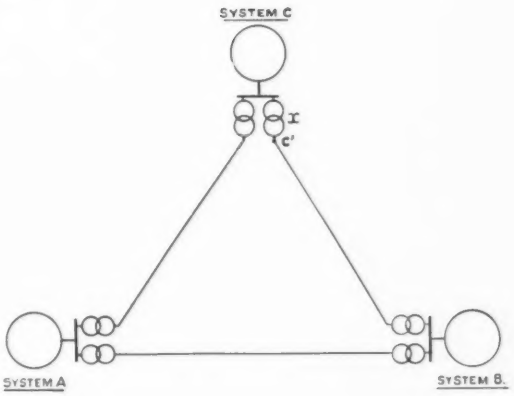


Fig. 3. Three interconnected power systems

Three Power Systems

In the case of three power systems interconnected as shown in Fig. 3, the power flow over any one of the tie-lines cannot be individually controlled by adjustment of the power output of the prime movers and generators. Any attempt to adjust the load in the line AB by altering the governor settings at A or B would also result in a change of load in the lines AC and BC.

Consider the line BC out of circuit and System A supplying power to System B but not to System C, the generation at C being just sufficient to supply its own load. In order that power shall not flow between A and C the terminal voltage of these two systems must be similar in magnitude and phase. A difference will then exist in the phase and probably in the magnitude of the voltage between B and C. If the line interconnecting them were closed there would be a flow of active and reactive power along it, giving a redistribution of power in the other lines. Assuming the various generator outputs and loads remained constant, the load flow in AB would be decreased and part of the output from A would flow along the lines AC and CB. This redistribution of power would depend entirely on the relative impedances of the three lines.

If before closing the tie-line BC, adjustment of the transformer ratio at 'x' were made by the normal in-phase voltage tappings, the magnitude of the voltage at c′ could be made equal to that at the other end of the line and on closure the

reactive power flow between B and C would be negligible. There would still, however, be real power transferred due to the phase angle difference. Therefore, to reduce the flow of MW in the line it is necessary to adjust the phase of the voltage by introducing a quadrature component of voltage, and a quadrature booster transformer can be employed for this purpose. Thus, where there are three or more power systems interconnected, in order to adjust the power flow in any one line it is necessary to have both 'in-phase' and 'quadrature' voltage control.

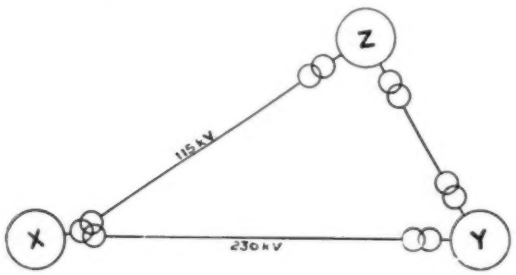


Fig. 4. A large generating station, or group of stations, connected to two load centres by long H.V. lines

A common example of this is shown in Fig. 4 where X, which represents a large generating station or group of stations, is connected by long high-voltage lines to the load systems Y and Z, of which Y is the larger. Due to consideration of voltage regulation it might be desired to transmit the power to Y by both routes in a proportion different from that of the natural flow, or for economic reasons to maintain the loading in the 230 kV line at a high level. Either of these objects can be attained by the installation at X of a transformer provided with in-phase and quadrature voltage adjustment on one of the H.V. windings.

Parallel Lines

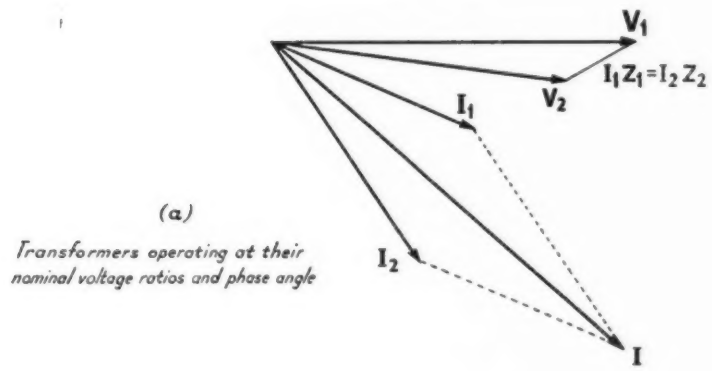
It is often necessary due to the growth of a power system to erect an additional line in parallel with an existing tie-line. In many cases the new line will be designed to have a larger load-carrying capacity and may possibly be for a different voltage than the original line. It is unlikely that the natural division of load between the two lines will be that desired, and some additional equipment must be installed to obtain the required condition. Again the quadrature booster transformer can be used.

As a simple illustration of this, the case is now considered where an existing 66 kV line 20 miles in length has been reinforced by a 132 kV line connected through transformers to the 66 kV line terminal busbars. This is represented in Fig. 5. The quantities have been calculated fully, using typical line and transformer constants and taking into account the resistance of the line. The transmitted power has been taken as approximately 100 MW at 0.8 p.f., and for convenience in comparison of the vector diagrams the power at the sending end of the two lines has been assumed constant. The voltage drops along the lines are somewhat larger than would be found in practice, but this has been done deliberately by assuming the transmission of a large amount of power in order to magnify the effects produced.

In Fig. 5d a single-line diagram is shown, and Fig. 5e gives the equivalent impedance diagram on a 66 kV base. It is assumed that Transformer No. 1 is equipped with in-phase voltage tappings and a quadrature booster ; the effects of these are represented on the impedance diagram by a voltage $v_d + jv_q$ injected into the circuit, the voltage at the sending end (V_1) being taken as a reference vector.

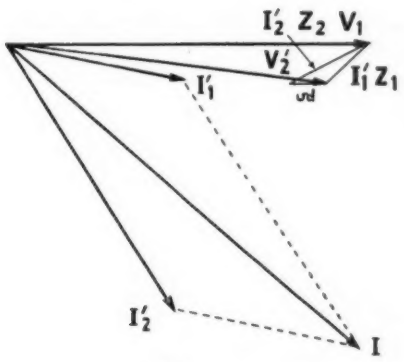
With both transformers operating at their nominal voltage ratio of 66/132 kV, and without any quadrature boost from Transformer No. 1, the division of current between the two lines is as shown in Fig. 5a. It will be noticed that although the current I_2 is slightly the larger, more active power is being transmitted down the 66 kV circuit. Since the load capacity of the 132 kV circuit is the greater, this condition of power division could be changed over with operational and economic advantages.

The effect of increasing the voltage ratio of Transformer No. 1 by 10% with the in-phase voltage tappings is shown in Fig. 5b. The alteration of the H.V. tapping is represented by the inclusion of the vector v_d in phase with V_1. The voltage difference between the terminal busbars now being equal to I'_1Z_1 and also to $I'_2Z_2 - v_d$, the natural



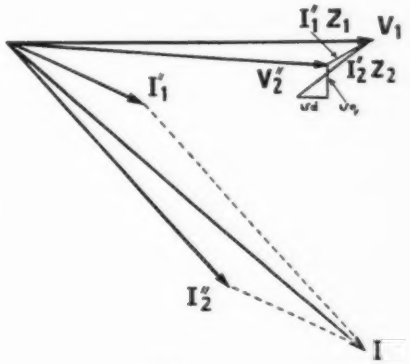
(a)

Transformers operating at their nominal voltage ratios and phase angle



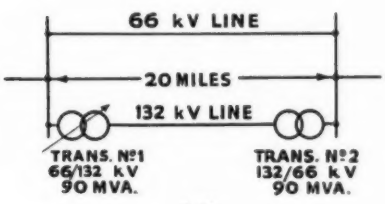
(b)

Transformer No1 with H.V. in-phase topping + 10% and H.V. quadrature boost nil.



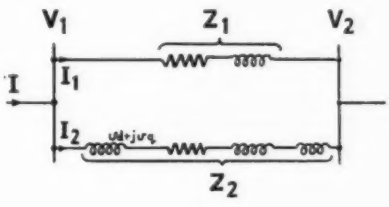
(c)

Transformer No1 with H.V. in-phase topping + 10% and H.V. quadrature boost 10%.



(d)

System diagram.



(e)

Impedance diagram referred to 66 kV system voltage.

Fig. 5. Vector diagrams for two parallel inter-connectors operating at different voltages

division of the current has been altered. The changes in power factors due to increased reactive power in the 132 kV line are very noticeable, I'_2 being now nearly twice I'_1. There is also a slight difference in the division of the active power in the two lines, but the 66 kV line still carries most. This has not solved the problem of the division of active power, although the transmission losses would be slightly less due to the smaller current in the 66 kV line.

Fig. 5c shows the effect of introducing a voltage at Transformer No. 1 that is in quadrature with V_1 and equal to 10% of the nominal H.V. value, in addition to the in-phase voltage previously introduced. This is represented by the vector v_q which, in conjunction with v_d, makes up the difference between the vectors representing I''_1Z_1 and I''_2Z_2.

As would be expected from the foregoing, this results in a large variation in the division of active power : the amount of active power flowing in the 66 kV circuit is reduced to about two-thirds of its original value and is now approximately 60% of that in the 132 kV circuit. This division may not yet be the best possible but it is of the right order. The magnitude of the injected voltage would need to be varied slightly until optimum conditions were obtained.

It will be noticed that the quadrature booster does vary the reactive power very slightly as well as the active power and, conversely, the in-phase voltage variation has a slight effect on the active power. This interdependence is due to the fact that the impedance of the transmission circuits is not purely reactive but also includes some resistance. The predominant effect, however, is still that the quadrature voltage varies the active component and the in-phase voltage the reactive component.

A Large Installation

The article which follows on the next page describes a large transformer installation equipped for both in-phase voltage regulation and phase-angle variation, representing an actual application of the principles of quadrature booster transformers which the present article has discussed.

A Transformer Installation Incorporating On-load Tap-changing Equipment for In-phase Voltage Regulation and Phase-angle Variation

By R. M. CHARLEY, M.C., B.Sc., M.I.E.E., Mem.A.I.E.E.

THE PRECEDING ARTICLE discussed the principles involved in the use of quadrature booster transformers in electric power systems.

This article describes a transformer installation, incorporating quadrature boosting or phase-angle regulating equipment, that is unique in several respects : it is probably the largest of its kind ever built in the United Kingdom, for the five units comprising the complete equipment are complementary one to the other and must be considered as an indivisible whole. The size of this installation may be appreciated from the fact that the total weight including oil is about 520 tons and the present-day cost about £210,000.

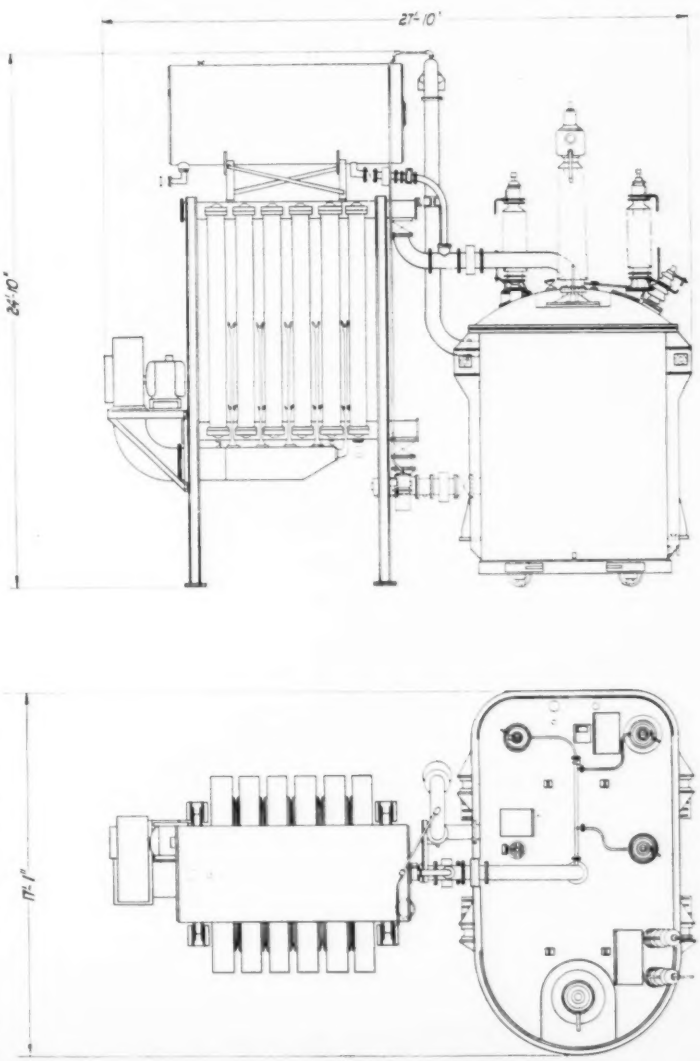


Fig. 1. *General arrangement of one single-phase unit of* 90 *MVA bank*

Purpose and Arrangement

The purpose of the transformer installation is to take a supply from a 220 kV system and to deliver power to networks operating at 115 kV and 38.5 kV. The main transformer is formed of a bank of three single-phase units, the H.V. and M.V. windings being arranged for star connection at 220 kV and 115 kV respectively, and having a capacity of

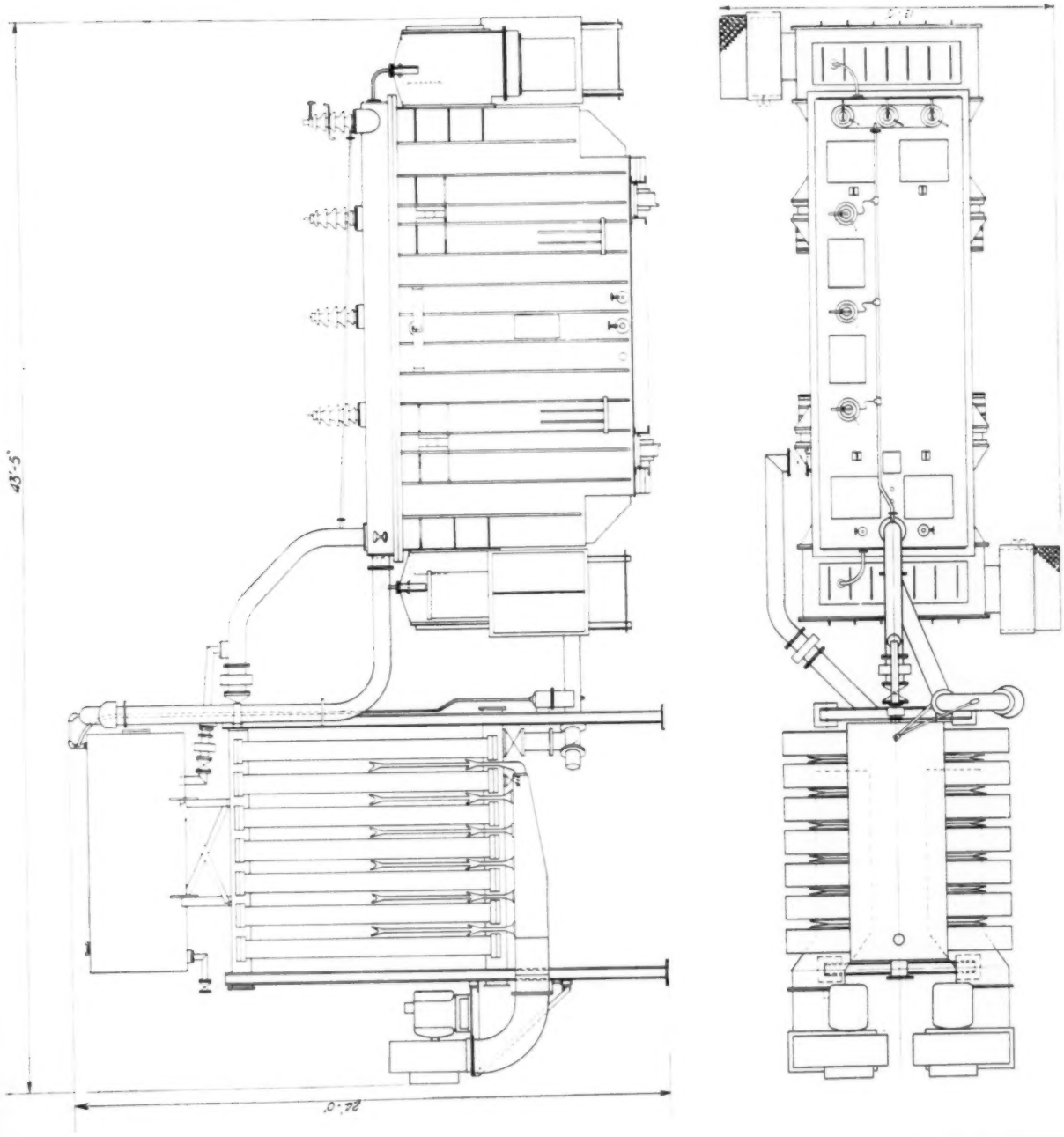


Fig. 2. General arrangement of potential unit

90 MVA ; the L.V. windings are delta connected and have a capacity of 60 MVA. On the 220 kV winding, tappings are provided for $+2\frac{1}{2}\%$, $-2\frac{1}{2}\%$, -5% and $-7\frac{1}{2}\%$, and are selected by a tapping-switch for off-circuit operation. The outline of a single-phase unit of the main transformer is shown in Fig. 1.

In relation to the 115 kV winding the specification called for in-phase voltage regulation of + and − 12%, and phase-angle variation of 15 degrees lead,

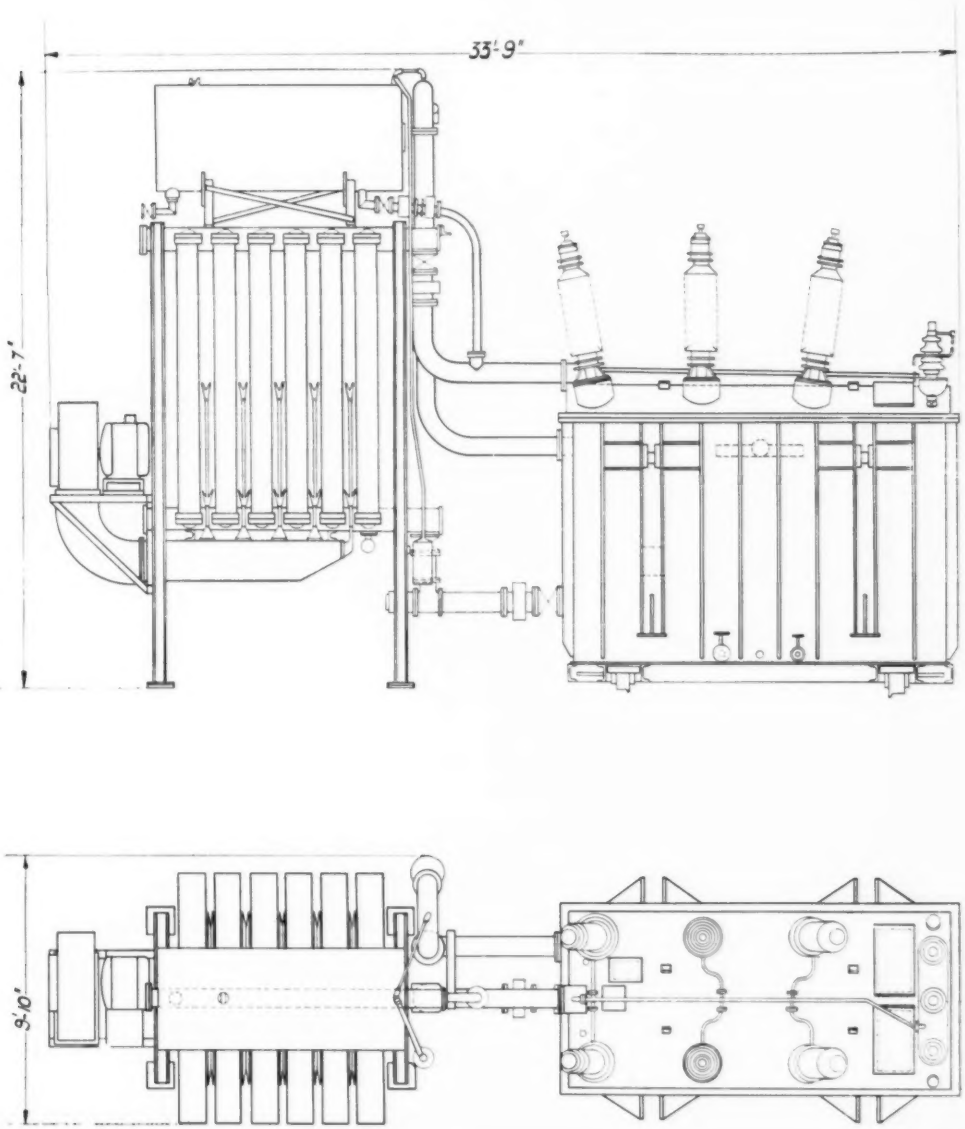


Fig. 3. General arrangement of series unit

Fig. 2. General arrangement of potential unit

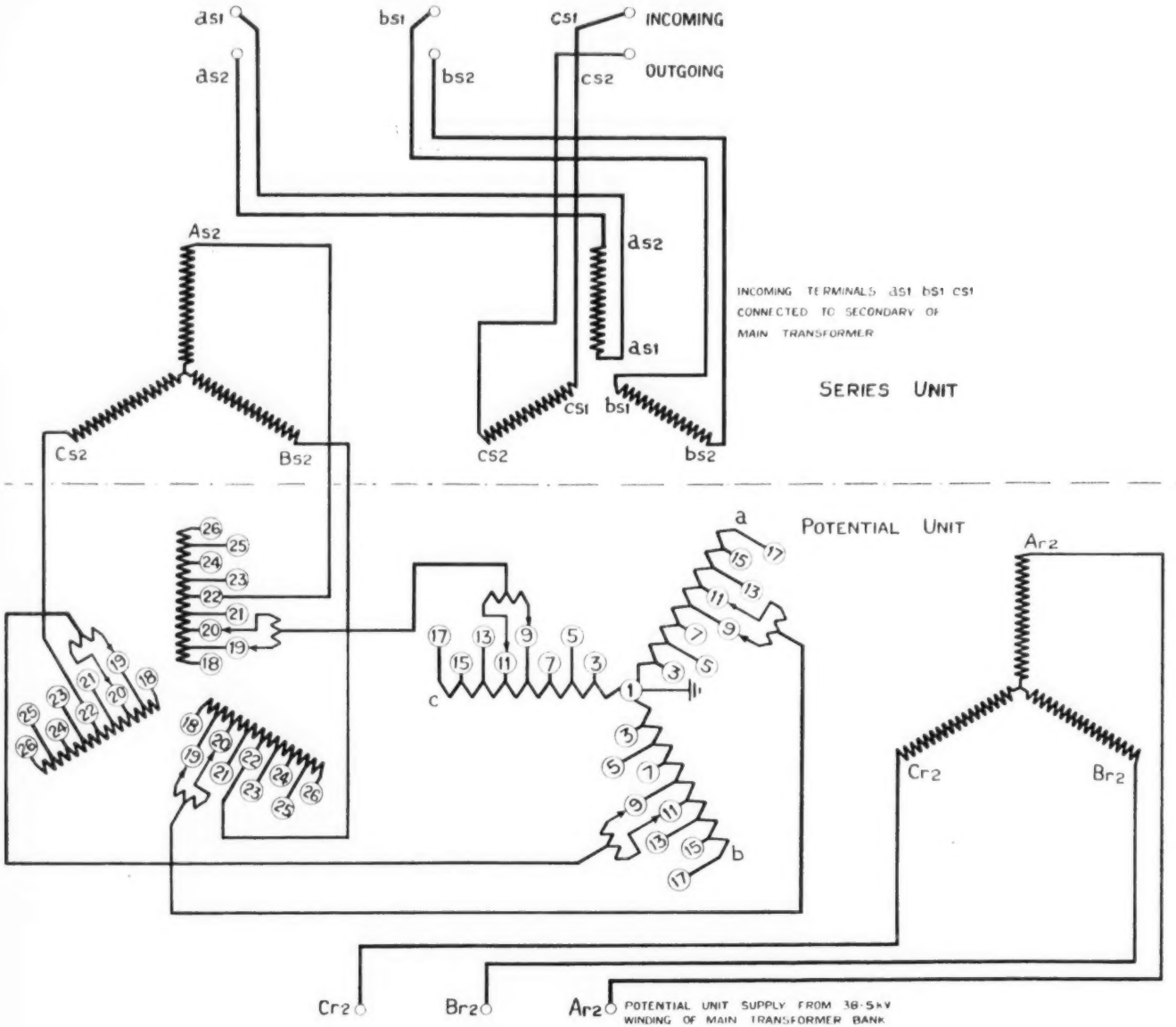


Fig. 4. Diagrammatic arrangement of windings for potential and series units

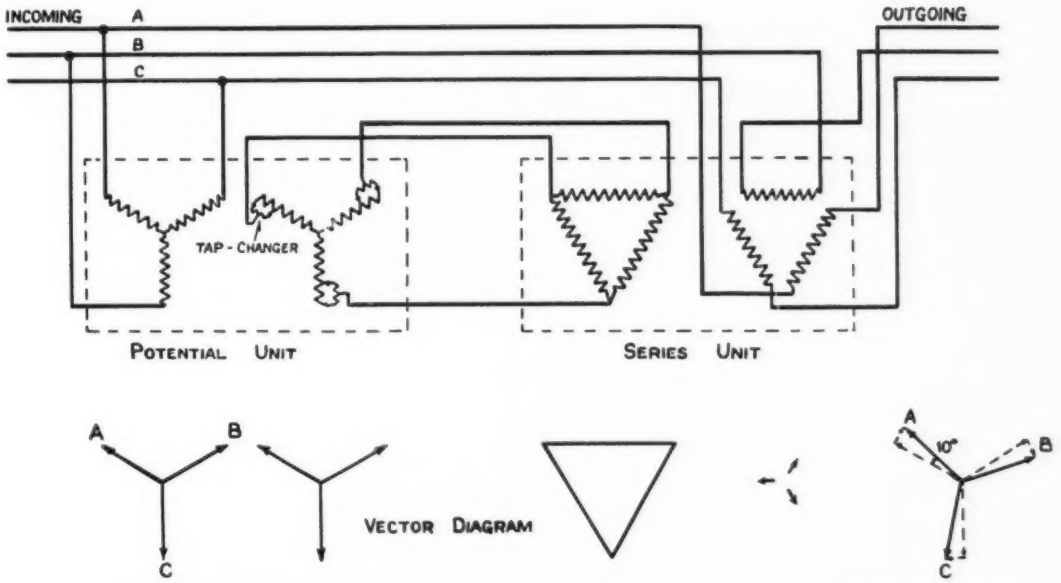


Fig. 5. Simple diagrammatic arrangement of windings, illustrating the principle of phase-angle variation

both operated by means of on-load tap-changing equipment, separately or in combination. This is achieved by the provision of a separate regulating transformer equipment comprising a potential unit and a series unit, each of the three-phase type, the outlines of which are shown in Figs. 2 and 3. The diagrammatic arrangement of this equipment and the vector relationship are shown in Fig. 4. The primary winding of the potential unit is arranged in star and is connected to the 38.5 kV winding of the main transformer ; there are two separate secondary windings each provided with a number of tappings connected to two separate on-load tap-changing equipments. From the combination of these two secondary windings connection is made to the primary winding of the series unit, the secondary winding of which is connected in series with the leads from the 115 kV winding of the main transformer.

On-load Tap-changing

On-load tap-changing for simple voltage regulation has been common practice in the United Kingdom for nearly thirty years, and transformers so equipped totalling many millions of kVA have been built. In more recent years the growth of networks and interconnection of systems have raised new problems, one of the most serious being a phase-angle difference between two points in a system when other points are connected together. This characteristic can be corrected by the provision of regulating transformers in which the windings of the three phases are interconnected in such a manner as to produce a phase-shift, the amount of which is determined by the voltage induced as controlled by the on-load tap-changing equipment. This principle is illustrated in a simple and hypothetical manner in Fig. 5, in which example the phase-angle can be varied between zero and say, ten degrees.

As already mentioned, there are two separate secondary windings on the potential unit, each being tapped, so that through the medium of the on-load tap-changing equipment with the mid-point auto-transformer, seventeen operating positions are provided in connection with each winding. In Fig. 4 it will be seen that the middle point of each phase of the in-phase winding of the potential unit is connected to the line terminal of the star-connected primary winding of the series unit, and

Fig. 4. Diagrammatic arrangement of windings for potential

TABLE GIVING COMPLETE RANGE OF IN-PHASE VOLTAGES AND PHASE-ANGLE VARIATIONS AT NO-LOAD, REFERRED TO THE 115 kV WINDING.

Switch No. 1 Positions.	In-phase Kilovolts.	Amps.	SWITCH NO. 2 POSITIONS AND QUADRATURE VOLTAGES IN kV.															
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			+j 0	+j 1·93	+j 3·86	+j 5·79	+j 7·73	+j 9·66	+j 11·59	+j 13·52	+j 15·45	+j 17·38	+j 19·31	+j 21·25	+j 23·18	+j 25·11	+j 27·04	+j 28·97	+j 30·90
1	101·11	513	101·11 0°	101·13 1° 6′	101·18 2° 11′	101·27 3° 17′	101·40 4° 22′	101·56 5° 27′	101·77 6° 32′	102·01 7° 37′	102·29 8° 41′	102·60 9° 45′	102·94 10° 49′	103·31 11° 52′	103·74 12° 55′	104·19 13° 57′	104·66 14° 58′	105·18 15° 59′	105·73 17° 0′
2	102·84	505	102·84 0°	102·86 1° 5′	102·91 2° 9′	103·0 3° 14′	103·13 4° 18′	103·29 5° 22′	103·49 6° 26′	103·73 7° 30′	103·99 8° 33′	104·30 9° 36′	104·64 10° 39′	105·02 11° 41′	105·42 12° 43′	105·86 13° 44′	106·33 14° 44′	106·84 15° 44′	107·39 16° 44′
3	104·58	497	104·58 0°	104·60 1° 3′	104·65 2° 7′	104·74 3° 10′	104·86 4° 14′	105·03 5° 17′	105·22 6° 20′	105·45 7° 22′	105·71 8° 24′	106·01 9° 26′	106·35 10° 28′	106·72 11° 29′	107·12 12° 30′	107·55 13° 30′	108·02 14° 30′	108·52 15° 29′	109·05 16° 28′
4	106·32	489	106·32 0°	106·34 1° 2′	106·39 2° 5′	106·48 3° 7′	106·60 4° 10′	106·76 5° 12′	106·95 6° 14′	107·18 7° 15′	107·44 8° 16′	107·73 9° 17′	108·06 10° 18′	108·42 11° 19′	108·82 12° 18′	109·24 13° 17′	109·70 14° 16′	110·20 15° 15′	110·72 16° 13′
5	108·05	481	108·05 0°	108·07 1° 1′	108·11 2° 3′	108·20 3° 4′	108·83 4° 6′	108·48 5° 7′	108·68 6° 8′	108·89 7° 8′	109·15 8° 8′	109·43 9° 8′	109·76 10° 8′	110·12 11° 8′	110·52 12° 6′	110·92 13° 5′	111·37 14° 3′	111·87 15° 1′	112·38 15° 58′
6	109·79	473	109·79 0°	109·81 1° 0′	109·86 2° 1′	109·94 3° 1′	110·06 4° 2′	110·22 5° 2′	110·41 6° 2′	110·62 7° 2′	110·87 8° 1′	111·16 9° 0′	111·48 9° 59′	111·84 10° 58′	112·21 11° 56′	112·62 12° 53′	113·07 13° 51′	113·55 14° 48′	114·06 15° 44′
7	111·53	466	111·53 0°	111·54 1° 0′	111·60 1° 59′	111·67 2° 58′	111·80 3° 58′	111·94 4° 57′	112·13 5° 56′	112·34 6° 55′	112·59 7° 53′	112·87 8° 51′	113·19 9° 49′	113·58 10° 47′	113·92 11° 45′	114·32 12° 41′	114·77 13° 38′	115·23 14° 34′	115·74 15° 29′
8	113·26	459	113·26 0°	113·27 0° 59′	113·33 1° 57′	113·41 2° 56′	113·52 3° 54′	113·67 4° 53′	113·85 5° 51′	114·07 6° 48′	114·31 7° 46′	114·59 8° 44′	114·90 9° 41′	115·25 10° 38′	115·62 11° 35′	116·01 12° 30′	116·44 13° 26′	116·91 14° 21′	117·40 15° 16′
9	115·0	452	115·0 0°	115·01 0° 58′	115·07 1° 55′	115·15 2° 53′	115·26 3° 51′	115·40 4° 48′	115·59 5° 45′	115·79 6° 42′	116·03 7° 39′	116·31 8° 36′	116·61 9° 32′	116·94 10° 28′	117·31 11° 24′	117·72 12° 19′	118·14 13° 14′	118·59 14° 8′	119·07 15° 2′
10	116·74	445	116·74 0°	116·75 0° 57′	116·81 1° 54′	116·88 2° 50′	116·98 3° 47′	117·14 4° 44′	117·31 5° 40′	117·52 6° 36′	117·75 7° 32′	118·03 8° 28′	118·33 9° 24′	118·65 10° 19′	119·02 11° 14′	119·41 12° 9′	119·83 13° 3′	120·28 13° 56′	120·76 14° 50′
11	118·47	439	118·47 0°	118·48 0° 56′	118·53 1° 52′	118·61 2° 48′	118·72 3° 44′	118·86 4° 40′	119·04 5° 35′	119·24 6° 30′	119·47 7° 25′	119·74 8° 20′	120·04 9° 15′	120·36 10° 10′	120·72 11° 4′	121·09 11° 58′	121·53 12° 52′	121·96 13° 44′	122·43 14° 37′
12	120·21	432	120·21 0°	120·22 0° 55′	120·27 1° 50′	120·35 2° 46′	120·46 3° 41′	120·61 4° 37′	120·76 5° 30′	120·97 6° 25′	121·19 7° 19′	121·46 8° 13′	121·75 9° 7′	122·07 10° 1′	122·42 10° 55′	122·77 11° 48′	123·22 12° 41′	123·65 13° 33′	124·12 14° 25′
13	121·95	426	121·95 0°	121·96 0° 54′	122·01 1° 49′	122·08 2° 43′	122·19 3° 38′	122·33 4° 32′	122·50 5° 26′	122·69 6° 20′	122·92 7° 13′	123·18 8° 7′	123·47 9° 0′	123·79 9° 53′	124·13 10° 46′	124·51 11° 38′	124·91 12° 30′	125·34 13° 22′	125·81 14° 13′
14	123·68	420	123·68 0°	123·69 0° 54′	123·74 1° 47′	123·82 2° 41′	123·93 3° 35′	124·05 4° 28′	124·22 5° 21′	124·41 6° 14′	124·64 7° 7′	124·89 8° 0′	125·18 8° 52′	125·50 9° 45′	125·83 10° 37′	126·20 11° 29′	126·60 12° 20′	127·03 13° 11′	127·49 14° 2′
15	125·42	415	125·42 0°	125·43 0° 53′	125·48 1° 46′	125·56 2° 39′	125·66 3° 32′	125·80 4° 24′	125·96 5° 17′	126·15 6° 9′	126·36 7° 1′	126·61 7° 53′	126·90 8° 45′	127·21 9° 37′	127·54 10° 28′	127·90 11° 19′	128·30 12° 10′	128·72 13° 0′	129·18 13° 50′
16	127·16	409	127·16 0°	127·17 0° 52′	127·22 1° 44′	127·29 2° 36′	127·40 3° 29′	127·53 4° 21′	127·68 5° 12′	127·87 6° 4′	128·10 6° 56′	128·34 7° 47′	128·62 8° 38′	128·93 9° 30′	129·26 10° 20′	129·62 11° 10′	130·0 12° 0′	130·42 12° 50′	130·86 13° 40′
17	128·89	403	128·89 0°	128·90 0° 51′	128·94 1° 43′	129·02 2° 34′	129·12 3° 26′	129·25 4° 18′	129·41 5° 8′	129·60 5° 59′	129·82 6° 50′	130·06 7° 41′	130·33 8° 31′	130·63 9° 22′	130·95 10° 12′	131·31 11° 1′	131·17 11° 51′	132·10 12° 40′	132·54 13° 29′

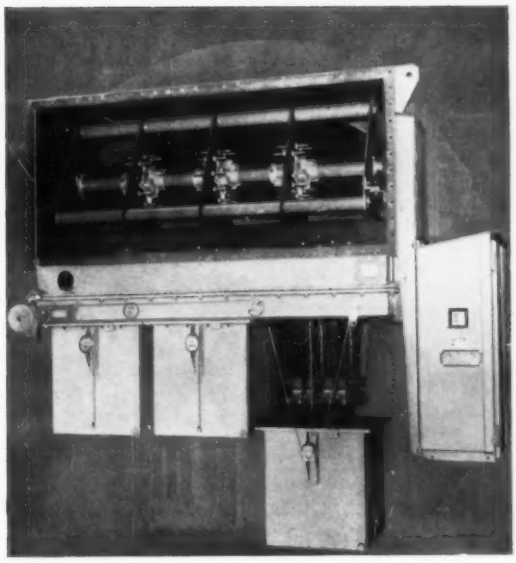


Fig. 6. On-load tap-changer

M.V. winding of 115 kV given with switch No. 1 in position 9, corresponds to a phase-angle of 15 degrees 2 minutes, and the vector relationship is such that the phase-angle of the 115 kV system is advanced by this amount. There is some slight change in the combined voltage resulting from the operation of the phase-angle on-load tap-changing equipment (switch No. 2) with each position of the in-phase equipment (switch No. 1). For example, with switch No. 1 in the normal position 9, the resulting output voltage is 115 kV with zero phase-angle variation (position 1 of switch No. 2), and it is 119.07 kV with 15 degrees 2 minutes phase-angle variation (position 17 of switch No. 2). Similarly, there is a change from 128.89 kV with zero phase-angle variation to 132.54 kV with 13 degrees 29 minutes variation. All voltages and phase-angles are calculated for no-load conditions.

The on-load tap-changing equipments, of which two are provided on the potential unit, are of the well-known ' English Electric ' type which has been embodied in transformers of all sizes and for all voltages and having a total capacity of about

the centre points of the two mid-point auto-transformers for each phase are connected together. Each secondary phase winding of the series unit is connected between a line terminal of the 115 kV winding of the main transformer and the terminal connected to the 115 kV transmission system.

The table on page 42 gives the complete range of in-phase voltages and phase-angle variations obtainable. The phase-angle winding gives certain voltages on the various tappings, as prefixed with the operator ' j ' at the top of the table, which, in combination with the fixed interconnection of phase windings, result in the phase-angle variations stated. For example, referring to switch No. 2 in position 17, the voltage of the phase-angle winding is 30.90 kV, which, on the normal voltage of the

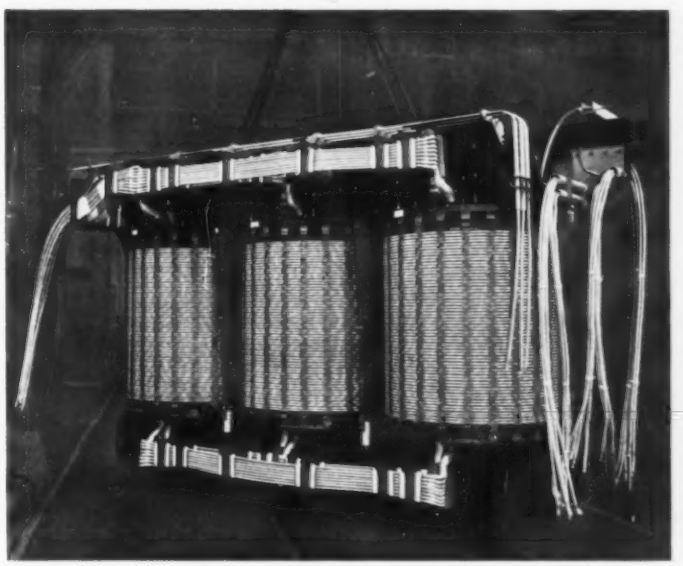


Fig. 7. Core and windings of potential unit

24 million kVA. An interesting feature is that the divertor switch of each phase is contained in a separate tank which can be lowered without draining off any oil, thus greatly simplifying the work of the maintenance engineer. This equipment is illustrated in Fig. 6.

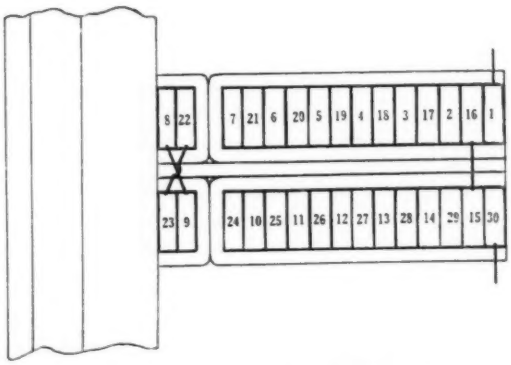


Fig. 8. Cross-section in diagrammatic form of double-section disc coil, showing interleaved arrangement

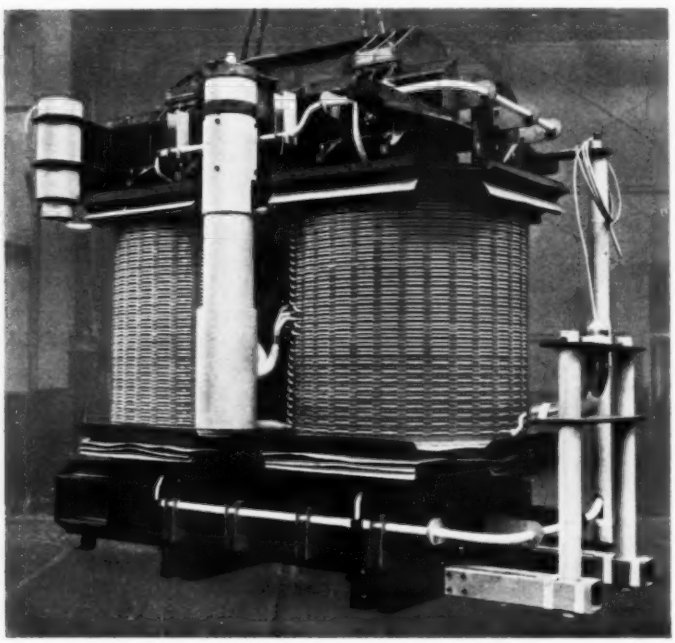


Fig. 9. Core and windings for one single-phase unit of 90 MVA bank

Windings

The tapped windings of the potential unit are each wound as a spiral winding covering the full length of the core, with eight layers, each layer forming a tapping section. In this manner all leads are taken from the ends of the winding, and for all tapping positions the symmetry of primary and secondary windings is so well maintained that mechanical forces under short-circuit are kept within reasonable limits. Fig. 7 shows the completely assembled core and windings of the potential unit.

The main transformer comprises a bank of three single-phase units. Each unit is built on a core of two-limb construction. There are three separate windings, for 220 kV, 115 kV and 38.5 kV, and for each voltage there is a coil on each limb, the two coils being connected in parallel. The 220 kV and 115 kV windings are formed on the 'English Electric' patented interleaved design, the important feature of which is that under impulse conditions oscillations are largely eliminated and the voltage distribution through the winding approaches a straight line. Fig. 8 shows a cross-section, somewhat in diagrammatic form, of a double-section interleaved coil, from which it can be seen that each pair of turns is separated by a turn electrically remote, e.g., turns 1 and 2 are separated by turn 16. The effect of this interleaving is greatly to increase the ratio between the series and shunt capacitances of the windings as compared with an arrangement using windings of the conventional pattern.

A complete core and windings for a single-phase unit of the main transformer is shown in Fig. 9.

The 220 kV system is operated with the neutral isolated but it is expected that the potential of the neutral above earth will never exceed 110 kV. Completely graded insulation cannot be adopted under this condition but reduced insulation is

applied at the neutral end of the winding. This feature required an unusual method of applying the insulation test which was carried out as follows : the 220 kV and 115 kV windings were connected in series, the 220 kV line terminal being isolated and the other 115 kV terminal being connected to earth ; a supply at 180 cycles per second was applied to the 38.5 kV winding and of such value that the voltage from the 220 kV line terminal to earth was 440 kV.

General

The losses of this transformer installation can be expressed in a variety of ways because the main

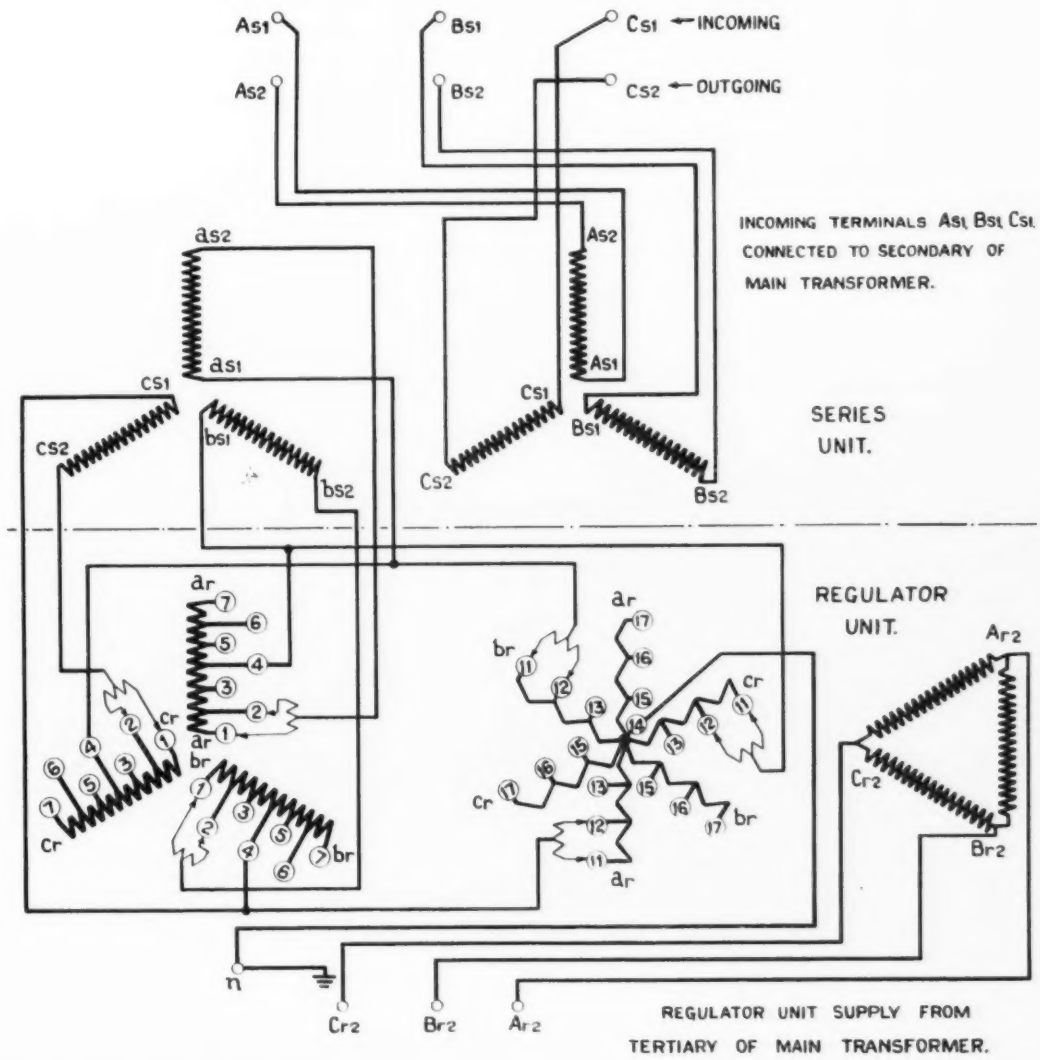


Fig. 10. Diagram of connections for a 35 MVA regulating transformer

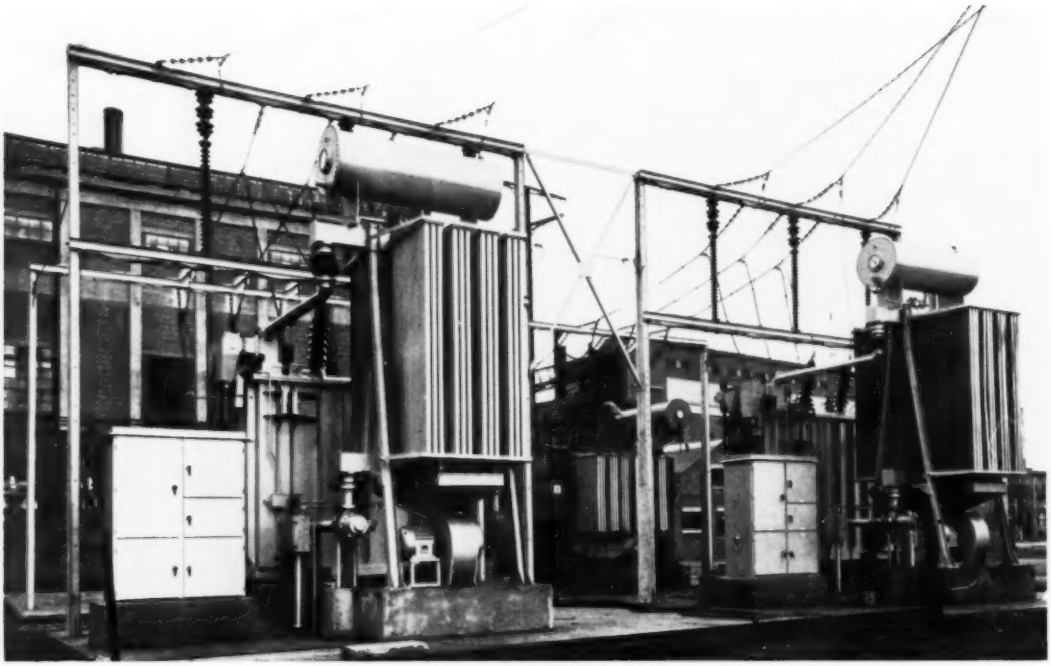


Fig. 11. *Site view of the two* 35 *MVA installations, with auto-transformers in foreground and regulating transformers behind*

unit has three windings and the losses of the potential and series units vary over a wide range. The iron loss of the 90 MVA main bank is 225 kW, and on the basis of the 220 kV and 115 kV windings being in service, the 38.5 kV winding being idle, the copper loss at 75°C. is 612 kW. Assuming that the main transformer is supplying power at 90 MVA through the regulating transformers at the normal voltage of 115 kV, and with zero phase-angle variation, the total loss is 1,100 kW.

Cooling of all units is of the ON/OFB type. The radiators, comprising nests of elliptical tubes welded into headers at top and bottom, are mounted on frames separate from the transformers. A pump is inserted in the main oil pipe and a fan is located beneath the radiators ; the motors of both pump and fan are brought into service automatically through the medium of the winding-temperature indicating equipment.

These transformers were delivered overseas in their own tanks but without oil. The process of emptying the tanks in the Works was carefully performed to ensure that they were finally sealed with dry air, after which it is anticipated that drying out on site will not be necessary. In filling the tanks with oil on site it is recommended for the main transformer, in which 220 kV windings are incorporated, that vacuum should be applied while the oil is allowed to enter, and that vacuum should be applied to all the transformers when completely filled with oil.

Another Installation

Another interesting application of a voltage and phase-angle regulating equipment is illustrated diagrammatically in Fig. 10. Two complete installations were supplied. Each comprises a 35 MVA auto-transformer having a voltage ratio of 68/34 kV with a delta connected tertiary winding for 7.6 kV, and a separate regulating transformer

consisting of a potential unit and series unit mounted in the same tank.

The delta connected primary winding of the potential unit is supplied from the 7.6 kV tertiary winding of the main auto-transformer ; there are two separate secondary windings each arranged for on-load tap-changing. Variable voltage is supplied from the combination of these two windings to the primary winding of the series unit, and each phase of the secondary winding of this unit is connected between the secondary terminals of the main auto-transformer and the 34 kV system.

On the assumption that the incoming pressure is 34 kV, No. 1 on-load tap-changing equipment varies the voltage from 32.3 kV to 35.7 kV in twelve steps, and No. 2 switch varies the voltage from plus 1,700 volts to minus 1,700 volts in twelve steps, corresponding to a phase-angle variation from 3 degrees lead to 3 degrees lag.

The total weight of this regulating transformer is 53 tons. The installation on site is illustrated in Fig. 11.